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Aquatic Plant Control Research Program

Selective Control of Eurasian Watermilfoil and Curlyleaf Pondweed in Noxon Rapids Reservoir, Montana

Aquatic Herbicide Evaluations, 2009-2010

Kurt D. Getsinger, John G. Skogerboe, John D. Madsen,
Ryan M. Wersal, Justin J. Nawrocki, Robert J. Richardson,
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Environmental Laboratory

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Abstract

A field demonstration was developed linking herbicide application methods with site-specific water exchange patterns to selectively control infestations of Eurasian watermilfoil (EWM) and curlyleaf pondweed (CLP) in Noxon Rapids Reservoir, MT. Objectives of this work are to evaluate species-selective control of these invasive plants employing innovative herbicide application techniques; and to provide recommendations for invasive plant management in the reservoir, and similar impoundments in the Pacific Northwest. Bulk water exchange patterns occurring in plant stands selected for herbicide applications were determined using rhodamine WT (RWT) tracer dye. These site-specific patterns were matched with appropriate herbicide application rates required to selectively control target plants. Treatments were conducted using a variable-depth injection system, simultaneously applying RWT and herbicides to provide maximum chemical contact time around plants stands. In late July 2009, two plots (8.2-11.5 ha) were treated using combinations of RWT (10 µg/L), triclopyr (1300 - 1850 µg/L), and endothall (1890 - 2500 µg/L). Dye (in situ) and herbicide residues (via enzyme-linked immunosorbent assay) were measured through the water column, inside and outside of the plots. Applications were conducted to coincide with the minimum reservoir discharge patterns. Whole plot water exchange half-lives ranged from 16 to 33 hr. Herbicide residues were highest around plants growing in the lower half of the water column (19-48 hr). External herbicide dissipation patterns were below levels of environmental/human health concerns. Treatments provided selective control of EWM for two years (> 85%) and CLP for one year (> 75%). Native plant species richness and dissolved oxygen levels were unchanged in treatment plots during the study period.

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Preface

The work reported herein was conducted as part of the Aquatic Plant Control Research Program (APCRP). The APCRP is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), and is assigned to the U.S. Army Engineer Research and Development Center (ERDC) under the purview of the Environmental Laboratory (EL), Vicksburg, Mississippi. Funding was provided under Department of the Army Appropriation No. 96X3122, Construction General, the Sanders County Eurasian Watermilfoil Task Force, and the Aquatic Ecosystem Restoration Foundation. The APCRP is managed under the Civil Works Environmental Engineering and Sciences Office, Dr. Alfred F. Cofrancesco, Technical Director. Dr. Linda S. Nelson was Program Manager of the APCRP. Program Monitor during this study was Timothy R. Toplisek, HQUSACE.

The Principal Investigator for this work was Dr. Kurt D. Getsinger, Environmental Processes Branch (EPB), Environmental Processes and Engineering Division (EPED), EL. This work was conducted and the report prepared by Dr. Getsinger and John G. Skogerboe, EPB; Drs. John D. Madsen and Ryan M. Wersal, Geosystems Research Institute, Mississippi State University, Starkville, Mississippi; Justin J. Nawrocki and Dr. Robert J. Richardson, Crop Science Department, North Carolina State University, Raleigh, North Carolina; and Morgan R. Sternberg, School of Aquatic and Fisheries Science, University of Washington, Seattle, Washington.

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- US Army Corps of Engineers Aquatic Plant Control Research Program.
- Sanders County Eurasian Watermilfoil Task Force:
    - Sanders County Commissioners
    - Montana State University Extension Service/Sanders Co.
    - Montana Department of Agriculture
    - Avista Utilities
    - Montana Fish Wildlife and Parks
    - Noxon Cabinet Shoreline Coalition
    - Green Mountain Conservation District
    - US Forest Service
    - Confederated Salish and Kootenai Tribe
    - Tri-State Water Quality Council

    - Sanders County Weed District

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Technical reviews of this report were provided by Dr. Chris Mudge and Angela Poovey, EPB. This work was performed under the general supervision of Dr. Beth Fleming, Director, EL; Warren Lorentz, Chief, EPED; and Mark Farr, Chief, EPB. At the time of publication of this report, Dr. Jeffery P. Holland was Director of ERDC. COL Kevin J. Wilson was Commander.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
knots	0.5144444	meters per second
miles (nautical)	1,852	meters
miles (U.S. statute)	1,609.347	meters

1 Introduction

Background

Noxon Rapids Reservoir, located in northwestern Montana, is one of several large run-of-the-river impoundments on the Lower Clark Fork River system. The reservoir stretches for over 30 linear miles, with its upstream boundary at the town of Thompson Falls, Montana. The reservoir has a surface area of ~ 3,100 ha (7,700 acres), with its widest fetch at 4 km across. The average depth of the reservoir is 20 m. The primary function of Noxon Rapids Reservoir is for hydro-electric power generation, managed by Avista Utilities. Daily dam operations are fairly consistent, but are dependent upon power demands in the regional power grid. Water discharge from the dam during summer months is typically a minimal 50-100 cubic feet per second (cfs) during night-time hours (1100 – 0800 hr), followed by a rapid increase in water release to maximum discharges of 26,000-27,000 cfs between 0900-1000 hr associated with peak power demand in the region (Avista Utilities, unpublished data). Note: Discharge data in this report are presented as cubic feet per second, rather than a metric equivalent.[1]

While the average depth of the reservoir is 20 m, the littoral zone consisting of some 800 ha has been defined from frequent surveys of water transparency and depth distribution of submersed plants, and can extend to depths of 10 m (Madsen and Wersal 2009). These surveys showed a diverse aquatic plant community with over 17 species reported in the reservoir. Dominant native plant species included elodea (*Elodea canadensis*), sago pondweed (*Stuckenia pectinata*), leafy pondweed (*Potamogeton foliosus*), and coontail (*Ceratophyllum demersum*). Species richness was relatively high, with an average of 2.25 species per survey point, with native species richness at 1.91 species per survey point (Madsen and Cheshier 2009).

During previous vegetation surveys on the reservoir, the invasive species were a relatively small component of the plant community, with an average of 0.35 exotic species per point (Madsen and Wersal 2008). Curlyleaf pondweed (*Potamogeton crispus*) occurred most often at 20% of surveyed points, followed by Eurasian watermilfoil (*Myriophyllum spicatum*) at 12.3% of littoral points, and flowering rush (*Butomus umbellatus*) at 2.3%

[1] A table of unit conversion factors for converting English units to metric units is presented on page xi.

of points. Vegetation was prevalent in all depths in the litoral zone - out to 4.5 m, common out to 6 m, and present to 7 m. Flowering rush was found in depths from 0.3 to 4.3 m. Eurasian watermilfoil was found in depths of 1.5 to 4.9 m, with an optimal depth of 2.4 to 3.5 m. Curlyleaf pondweed was found in depths from 0.6 to 4.9 m, with an optimal range of 1.2 to 3.4 m. In 2008, vegetation was estimated at 162 ha of curlyleaf pondweed, 100 ha of Eurasian watermilfoil, and 19 ha of flowering rush. A subsequent survey conducted in 2009 reported that Eurasian watermilfoil covered an estimated 147 ha, indicating that this species was expanding within the reservoir (Wersal et al. 2009).

Pursuant to the growing invasive plant problems facing Noxon Rapids Reservoir, i.e. Eurasian watermilfoil and curlyleaf pondweed, Sanders County and the Eurasian Watermilfoil Task Force identified a need to evaluate management strategies for controlling both invasive plant species. This document describes a two-year field demonstration that focuses on linking herbicide application methods with site-specific water exchange patterns to selectively control infestations of Eurasian watermilfoil and curlyleaf pondweed in the reservoir.

Objectives

The primary objectives of this work are to:

1. Evaluate species-selective control of the submersed invasive plants Eurasian watermilfoil and curlyleaf pondweed, employing innovative herbicide application techniques in Noxon Rapids Reservoir.
2. Utilize results of these evaluations to provide recommendations for submersed invasive plant management on Noxon Rapids Reservoir, and similar run-of-the-river impoundments in the Pacific Northwest.

To achieve these primary objectives, a series of evaluations were undertaken to:

1. Determine the bulk water exchange processes occurring in submersed plant stands selected for herbicide applications.
2. Link those site-specific water exchange processes to selection of appropriate herbicides and application rates required to selectively control the target plants.

3. Determine herbicide concentration and exposure time (CET) relationships within the treated plant stands, and dissipation of herbicide residues downstream from the treated areas.
4. Link those herbicide CET relationships to treatment effectiveness on target plants and to impacts on the overall submersed plant community in the treated areas.
5. Assess the performance of an innovative variable-depth herbicide application technique.

Details of the conduct, results, and implications from each of the evaluations listed are addressed in the various chapters of this report.

2 Linking Bulk Water Exchange Processes to Herbicide Use Patterns to Control Invasive Plants in Noxon Rapids Reservoir: July 2009

The success or failure of an herbicide treatment designed to control submersed plants will primarily depend upon two factors:

1. The concentration of the herbicide in water that surrounds the target plant.
2. The length of time the target plant is exposed to dissipating concentrations of that herbicide.

This dose/response phenomenon is herbicide- and target plant-specific, and has been defined as a concentration and exposure time (CET) relationship (Getsinger et al. 1996, Getsinger and Netherland 1997).

Hydrodynamic processes driven by gravity flow (rivers, streams, canals), tides (coastal waters and estuaries), and wind and thermal circulation patterns (lakes and reservoirs) impact bulk water exchange in submersed plant stands, and alter herbicide CET relationships. Thus, hydrodynamic processes can play a major role in determining success or failure of a treatment. For instance, chemical applications to entire water bodies (i.e. whole-lake treatments) routinely provide adequate plant control - since target plants are exposed to lethal concentrations of herbicides for sufficient time periods. In other words, a lethal CET threshold level has been achieved and plants are controlled.

However, reduced efficacy can occur in systems where only portions of the water body are treated (i.e. partial-lake treatments or spot treatments) and where water exchange processes in and around those treatment zones rapidly impact herbicide contact time in the vicinity of target plants. In other words, the lethal CET threshold level is never met, and target plants are not adequately controlled.

In submersed plant stands, water exchange processes are complex, subtle, and difficult to characterize. In these situations, inert fluorescent dyes can

provide an estimate of bulk water exchange and can be used to predict real-time, post-treatment dispersion/dissipation of liquid and granular aquatic herbicides. When coupled with known herbicide CET relationships, results from this tracer dye technique can be used to develop prescription treatment strategies where the appropriate herbicide, formulation (liquid or granular), application technique, and dose are used to overcome impacts of water exchange, and to provide desired and selective control of target plants.

Over the past 20 years, operational-scale treatments at various locations across the United States have verified that the linkage of water-exchange information, herbicide CET relationships, and innovative application techniques greatly improve management of Eurasian watermilfoil and hydrilla (*Hydrilla verticilla* Royle) in large lakes, reservoirs, and rivers (Getsinger et al. 1997, 2008, in preparation; Poovey et al. 2004). Based on these field verifications, new standards have been developed for the environmentally sound management of submersed weeds in many areas of high water exchange previously proclaimed “unmanageable.” These factors (water exchange measurements, herbicide CET relationships, and variable-depth chemical application strategies) were linked in studies conducted in submersed plant stands on Noxon Rapids Reservoir. The objective of these studies was to evaluate the selective control of the target plants Eurasian watermilfoil and curlyleaf pondweed in selected areas of the reservoir using a combination of the aquatic herbicides triclopyr ([(3,5,6-trichloro-2-pyridinyl)oxy]acetic acid) and endothall (7-oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid). If aquatic herbicides are to be considered as a management tool for the Noxon Rapids Reservoir and similar run-of-the-river reservoirs, bulk water-exchange assessments should be conducted prior to chemical treatment to determine site-specific hydrodynamic processes. Understanding these water-exchange processes will improve the efficacy and cost-effectiveness of potential herbicide applications.

This chapter documents the bulk water exchange evaluations and aquatic herbicide applications conducted on Noxon Rapids Reservoir in July 2009. Results of these evaluations will be linked to aqueous herbicide CET relationships and herbicide treatment effectiveness, as discussed in Chapter 3 of this report.

3 Bulk Water Exchange Processes in Submersed Plant Stands

Objectives

The primary objective of this section of work was to determine bulk water exchange processes that occurred in mixed stands of submersed plants during different stages of reservoir operations and discharge patterns. Once determined, this water exchange information can be used to develop prescriptive herbicide application techniques (dose and product delivery) to maximize the species-selective control of target invasive plants such as Eurasian watermilfoil and curlyleaf pondweed.

A secondary objective was to utilize water exchange information, driven by reservoir operations and discharge patterns, to predict the aqueous distribution and off-site dissipation of herbicides applied to stands of submersed plants. This information can be used to design chemical applications that will minimize impacts to areas outside of treatment zones – including potential contamination of potable water intakes and damage to environmentally sensitive areas.

Material and methods

Water exchange was measured in situ with fluorometric instrumentation using the inert tracer dye, rhodamine WT (RWT), approved by the US Environmental Protection Agency (USEPA) for use in surface waters. At the nominal aqueous concentrations used for this study ($\leq$ 10 µg/L), RWT dye is harmless to humans, fish, and wildlife (Fox et al. 1991). This dye is routinely used in water tracing studies in the Pacific Northwest by Federal and state agencies. At the concentrations used, the pink-colored dye is practically invisible to the naked eye, but can be measured using calibrated fluorometers at concentrations as low as 0.1 µg/L (ppb).

Four plots (~ 8 ha in size each) were selected for evaluation (Figure 1) on Noxon Rapids Reservoir, and were all located on Avista Utilities property. Plots 1 and 3 were selected for the water exchange and herbicide treatments, and Plots 2 and 4 were designated as reference or control plots (i.e. no dye or herbicides were applied to these plots). Since dye was not applied to the reference plots (Plots 2 and 4), this section of the report will only cover

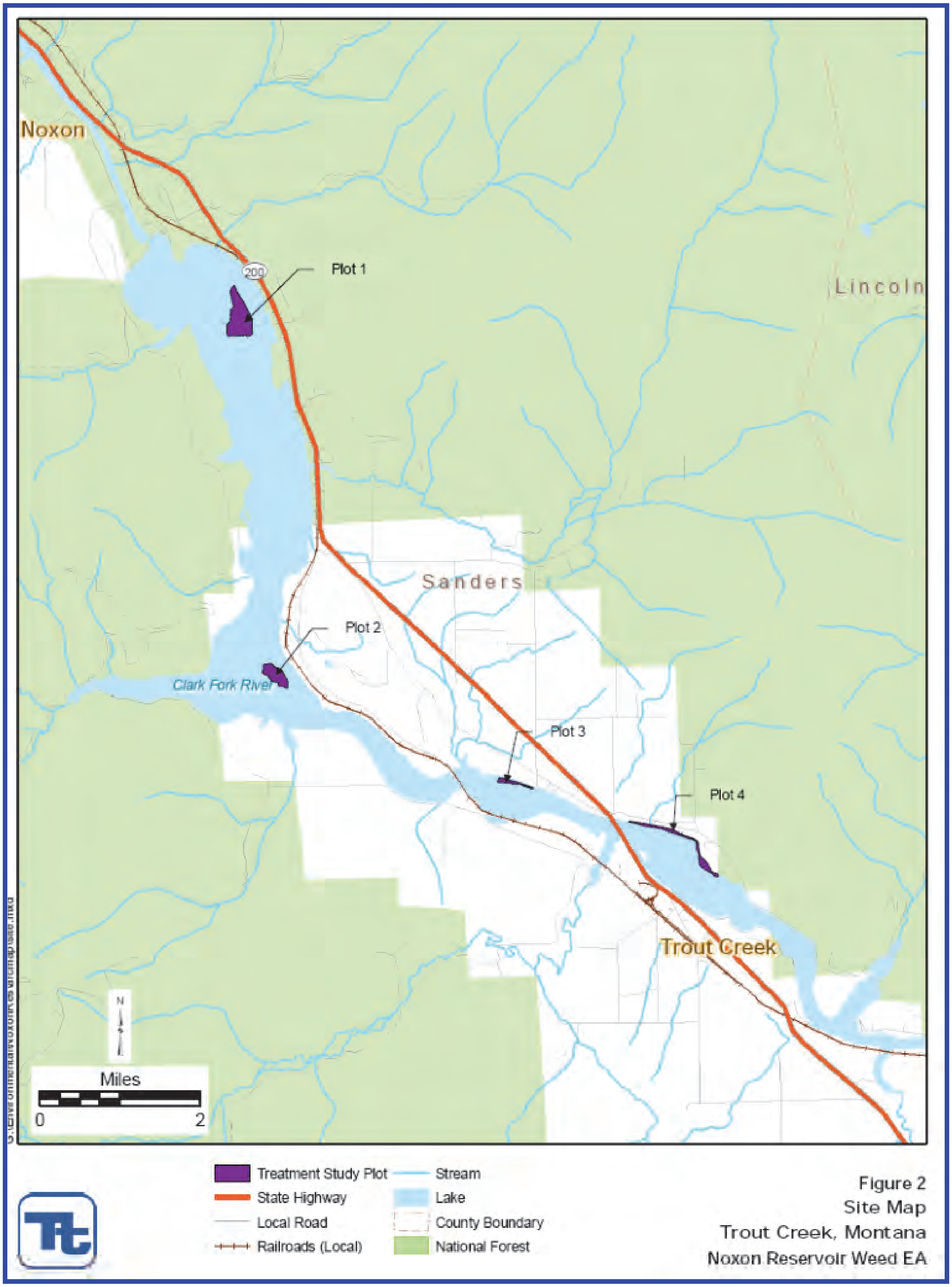

Figure 1. Plot locations on Noxon Rapids Reservoir, Montana, July 2009. Water flow is in a northwesterly direction.

details pertaining to the treatment plots (Plots 1 and 3). Plots 1 and 3 were each treated with dye at two different times. The initial application was with dye only. The second application followed several days later and involved a simultaneous application of dye plus a combination of liquid herbicides.

The liquid RWT dye was applied as either a tank mix with water, (or with water plus herbicide) using a variable-depth injection system (LittLine®) developed by Clean Lakes, Inc. (Coeur d'Alene, Idaho). This application process simulated an operational-scale liquid aquatic herbicide application, with the injection system calibrated to deliver product to the depth zone containing the targeted submersed plants. The RWT was applied at the rate of 10 µg/L, or 0.05 L of concentrated dye per acre-foot, based on the water volume of each plot.

Herbicides consisted of the contact product endothall (Aquathol® K, United Phosphorus, Inc.), and the systemic product triclopyr (Kraken®, Phoenix Environmental Care). Both liquid formulations were applied at rates designed to achieve selective control of the target plants Eurasian watermilfoil and curlyleaf pondweed. These nominal rates were 1850 µg/L (1.85 ppm) triclopyr and 2500 µg/L (2.5 ppm) endothall in Plot 1, and 1300 µg/L (1.3 ppm) triclopyr and 1890 µg/L (1.89 ppm) endothall in Plot 3. Herbicides were not applied as tank mixes. Application rates were based upon results of the initial water-exchange evaluations described below, and previously developed herbicide CET relationships (Netherland et al. 1991; Netherland and Getsinger 1992; Getsinger et al. 1997; Poovey et al. 2002, 2004; Skogerboe and Getsinger 2002).

Plot 1

Plot 1 was 8.2 ha in size, nearly square in shape (283 m x 285 m), and located on a submerged shelf (mean depth = 2.9 m) out in the open-water, lower region of the reservoir (Figure 2). The plot was ~ 500 m from the reservoir's east shore, ~ 150 m northeast of two small islands, and ~ 2300 m southeast and upstream of the dam and fore-bay area. The plot was treated with dye only on 23 July 2009 (wind S, 13-15 kph), and with dye + herbicides on 30 July 2009 (wind, calm). Fifteen permanent sampling stations were established for dye measurements (Figure 2), five internal (stations 20, 21, 22, 23, 25), and 10 external (stations 26-35). External stations ranged from 75 to 260 m from plot boundaries. Dye was measured in the water column at three depths: 0.3 m below the surface (S), mid-depth (M), and 0.3 m above the bottom (B) at each station.

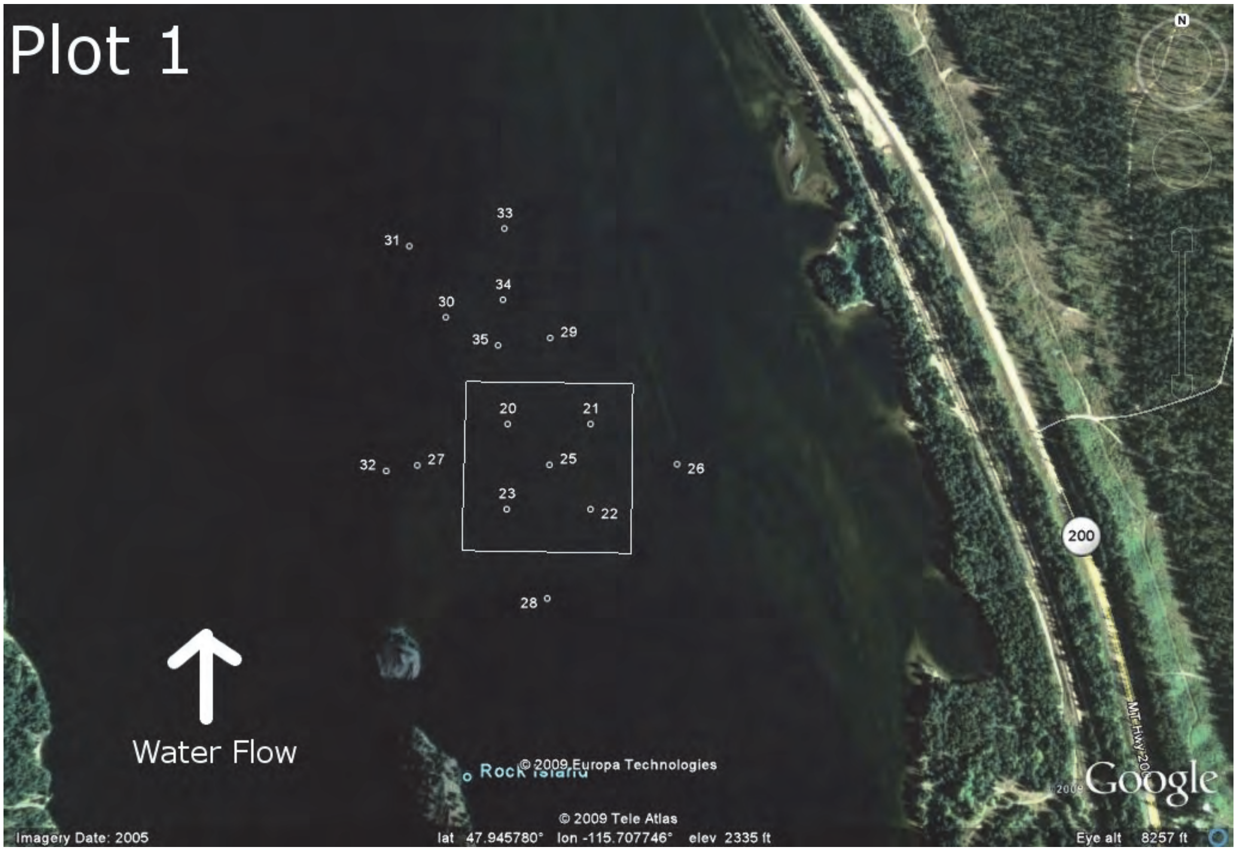

Figure 2. Plot 1 (8.2 ha), Noxon Rapids Reservoir, Montana, July 2009. Circles represent internal and external dye and herbicide sampling stations.

On 23 July, Plot 1 was treated evenly with dye, with the application starting at 0833 hr and ending at 0932 hr. Post-treatment water sampling events were conducted over time as follows: immediately after the entire plot had been treated, denoted as 0 hr after treatment (HAT), and at 1, 3, and 6 HAT. Average discharge for 23 July was 15,023 cfs (AVISTA, unpublished data).

On 30 July, Plot 1 was treated with dye + herbicides (triclopyr and endothall), with the plot being divided into three separate and equal application zones. Applications were delivered evenly over each zone until the entire plot was treated. This treatment process lasted approximately 50 minutes. The total application process started at 0200 hr and ended at 0622 hr. Approximately 1 hr elapsed during reloading of products between treatment of zones 1 and 2, and zones 2 and 3. Dye and herbicide were tank mixed and applied simultaneously. Post-treatment water sampling events were 0, 1, 3, 6, 8, 10, 12, 24, 33, and 48 HAT. Average reservoir discharge for 30 July was 13,847 cfs (Avista Utilities, unpublished data).

Plot 3

There were two versions of Plot 3. The initial version of Plot 3 (mean depth = 2.6 m) was 6.5 ha in size, rectangular in shape (70 m x 783 m), and used for the dye-only treatment (22 July 2009). However, this plot was subsequently enlarged to create a second version encompassing a rectangle 7.7 ha in size (100 m x 783 m) during the dye + herbicide treatments (28 July 2009). The 7.7-ha version was divided into two sub-treatment blocks: a shallow zone (4.5 ha, mean depth = 2 m) and a deeper zone (3.2 ha, mean depth = 3 m). Water exchange information from the initial version of the plot (the 6.5-ha dye application of 22 July) was used to enlarge the plot to the 7.7-ha version (sub-divided as blocks of 4.5 ha and 3.2 ha) for the dye + herbicide applications (28 July). The plot size was increased, based on the dye-only treatment of 22 July, to develop a more precise application strategy that was designed to improve herbicide contact time and efficacy. Both versions of the plot were situated along the north shore of the reservoir, approximately 14.5 km upstream of the dam (Figures 3 and 4).

Figure 3. The initial version of Plot 3 (6.5 ha), Noxon Rapids Reservoir, Montana, July 2009. Circles represent internal and external dye and herbicide sampling stations.

Figure 4. The revised and expanded version of Plot 3 (7.7 ha), Noxon Rapids Reservoir, Montana, July 2009. Circles represent internal and external dye and herbicide sampling stations.

Plot 3 was treated with dye only on 22 July (wind SE, 1-3 kph), and with dye + herbicides on 28 July (wind, calm). Sixteen permanent sampling stations were established for dye measurements (Figures 3 and 4), nine internal (stations 1-8, 15), and seven external (stations 9-14, 16). External stations ranged from 80 to 585 m from plot boundaries. Dye was measured in the water column at three depths: S, M, and B at each station.

On 22 July, the 6.5-ha Plot 3 was treated evenly with dye, with the application starting at 0752 hr and ending at 0824 hr. Post-treatment water sampling events were 0, 1, 3, 6, 9, 23, and 33 HAT. Average discharge for 22 July was 16,610 cfs (AVISTA, unpublished data).

On 28 July, the 7.7-ha Plot 3 was treated with dye + herbicide as two separate sub-plots, with an application split spread evenly over each sub-plot, and lasting approximately 50 min to 1 hr per split. The complete application process started at 1003 hr and ended at 1243 hr. Approximately 1 hr elapsed during re-loading of products between the application split. Dye and herbicide were tank mixed and applied simultaneously. Post-

treatment water sampling events were 0, 1, 2.5, 6, 7, 19, 46, and 68 HAT. Average reservoir discharge on 28 July was 13,938 cfs (AVISTA, unpublished data).

Data analysis

Water exchange (dye) half lives for all treated plots were determined using Sigma Plot 9.0, and subjected to a regression analysis using a sigmoid function. Dye dissipation patterns within, and outside of, treated plots were created with Surfer 7.04 using a Kriging grid method. Water-column distribution of dye is presented as a mean percentage dye measured in three depth zones (S, M, B), as described above.

Results and discussion

Plot 1

Whole-plot water-exchange half-life for the dye-only treatment (23 July) was very short, 2 hr, with little variation measured in the water column (Table 1). A steady southerly wind (13-15 kph) during the application process probably contributed to dye movement out of the plot, but reservoir discharge patterns, proximity of the plot to the dam, and location of the plot away from protected shorelines may have been major factors in bulk water exchange processes and subsequent dissipation of dye from the treatment area.

Table 1. Calculated water-exchange half-lives for plots treated with rhodamine WT dye in surface, middle, and bottom depth zones, and for the whole plot on Noxon Rapids Reservoir, Montana, July 2009.

			Dye Half Life (h)				
Plot	Date	Treatment	Surface	Middle	Bottom	Whole Plot	Respective R^2
Plot 1	7/23/2009	Dye	2	3	2	2	0.99, 0.99, 0.99, 0.99
Plot 1	7/30/2009	Dye & Herbicide	48	48	33	33	.96, .87, .86, .86
Plot 3	7/22/2009	Dye	9	9	5	7	.95, .99, .99, .99
Plot 3	7/28/2009	Dye & Herbicide	18	15	11	16	.87, .90, .91, .91

Figure 5 is an example of a late-July daily reservoir operations and discharge curve (23 July 2009). The discharge is essentially zero during early morning hours (0330–0830 hr), but accelerates rapidly from 0900–1100 hr (0 to 22,000 cfs), and remains high (22,000-25,000 cfs) until 2200 hr, when the steep discharge decline begins. This initial and large pull of water through the dam, reflecting the rapid increase in mid-morning power

demand, coincided with the dye application period (0833-0932 hr). Since discharge remains high for the 12 hr, it was expected that water movement (flow) patterns in the plot would continue to be high, resulting in a short water exchange half-life and a limited herbicide contact time around target plants. In fact, treating under this scenario resulted in a very short water-exchange half-life of 2 hr (Table 1).

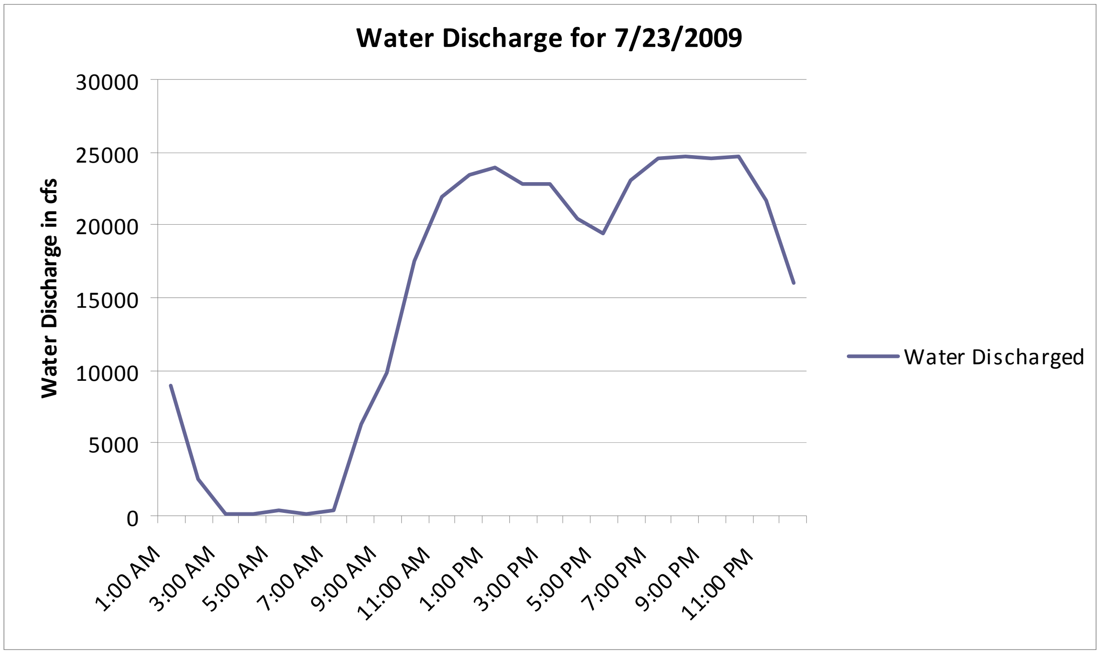

Figure 5. Water discharge pattern from Noxon Rapids Reservoir, Montana, 23 July 2009 (Avista Utilities, unpublished data) (1:00 am = 0100 hr; 1:00 pm = 1300 hr).

In an effort to decrease the water exchange half-life (and extend potential herbicide contact time), the 30 July application (dye + herbicide) was targeted for the minimum reservoir discharge pattern (slack water).Thus, the application was conducted between 0230 and 0630 hr. This approach resulted in extending the whole-plot water exchange half-life to 33 hr, a nearly fifteen-fold increase (Table 1). The greatly diminished water exchange occurring during slack water operation of the reservoir should translate into an extension of potential herbicide contact times around target plants, and acceptable efficacy. Herbicide contact time and target plant control will be verified with analyses of aqueous herbicide residues and the 1-year post-treatment vegetation assessment.

Aqueous distribution of dye suggested that the variable-depth application technique successfully injected product into the lower portions of the water column. Through 6 HAT on the 23 July treatment, 33-72% was

measured in the bottom zone and ~ 70-90% at mid + bottom (Figure 6), even though that treatment exhibited a short water-exchange half-life of 2.3 hr. However, on the 30 July application, which had a water exchange half-life of 33 hr, 53-92% was measured in the bottom zone for up to 10 HAT, and ~ 70-95% at mid + bottom (Figure 7). Placement of herbicides in and around target plant stands in the lower levels of the water column could be critical for achieving maximum efficacy.

Figure 8 depicts dye dissipation (simulating herbicide dissipation) in the bottom depth level at 6, 10, and 24 HAT. These patterns indicate that dye levels remained within the treated plot for prolonged periods. This should equate to prolonged herbicide exposure within the plot, resulting in effective control of target weeds.

Plot 3

Whole-plot water exchange half-life for the dye-only treatment (22 July) was 7 hr, with little variation measured in the water column (Table 1). The application time for this treatment (0752-0824 hr) was at the last phases of

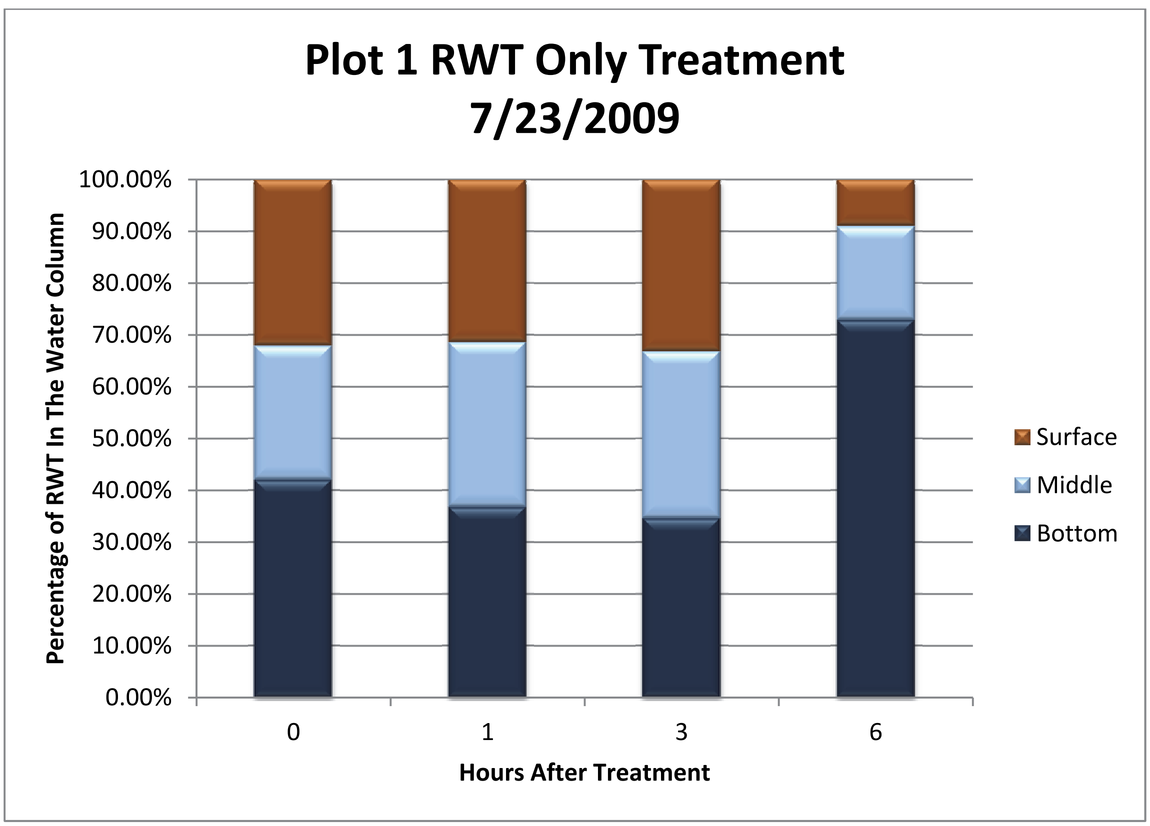

Figure 6. Water-column distribution of rhodamine WT (RWT) dye in Plot 1, Noxon Rapids Reservoir, Montana, 23 July 2009.

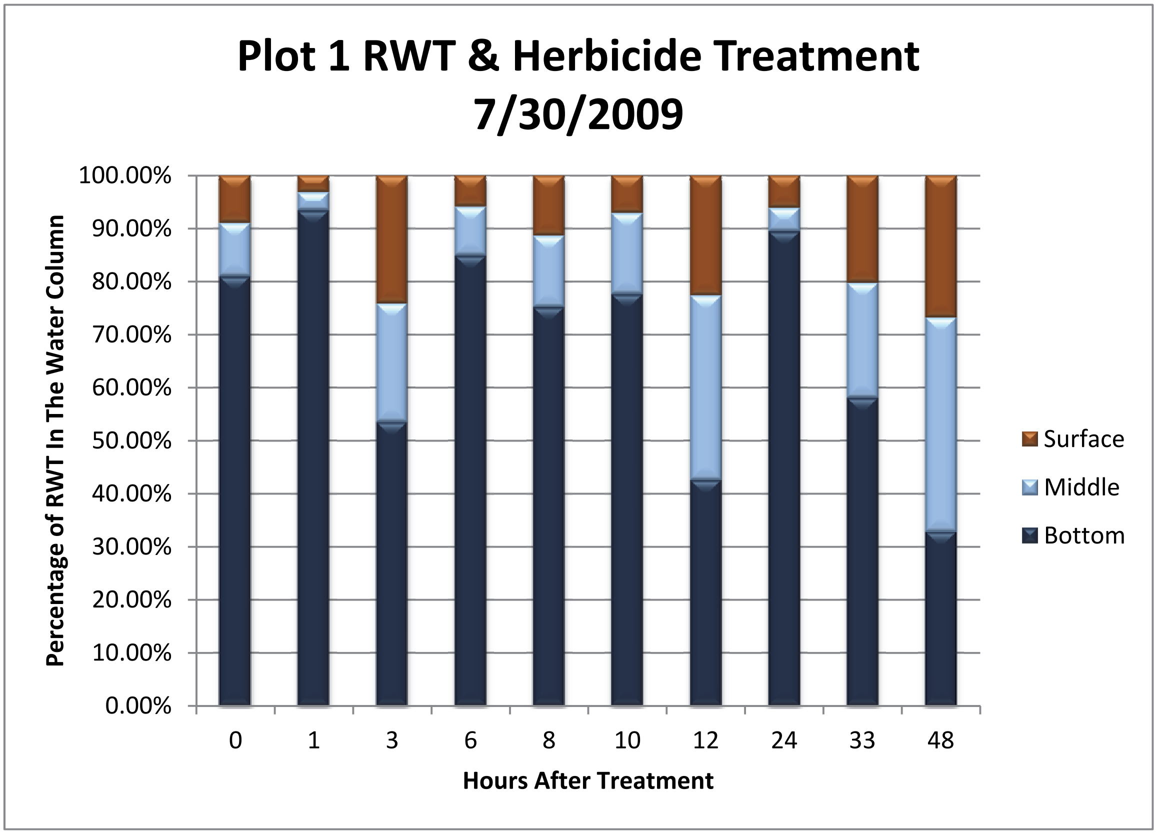

Figure 7. Water-column distribution of rhodamine WT (RWT) dye in Plot 1, Noxon Rapids Reservoir, Montana, 30 July 2009.

the slack-water, low-discharge period on the reservoir (Figure 5), which would somewhat favor an extension of potential herbicide contact time against targeted submersed plants. In addition, low winds during the application period, upstream distance (14.5 km) of the plot from the dam's discharge gates, and placement of the plot along the shoreline, rather than in open waters of the reservoir, probably aided in reducing water exchange patterns. But, as discharge rates increased rapidly within a few hours after treatment (0-32,000 cfs), water movement (flow) would eventually increase in the plot, driving water-exchange half-lives downward, and reducing potential herbicide contact time.

In an effort to increase the water exchange half-life (and extend potential herbicide contact time), the 28 July application (dye + herbicide) was targeted for a more stable reservoir discharge pattern, one that would avoid the rapid surge that typically occurs from 0900-1000 hr. Thus the treatment time was selected to occur after 1000 hr.

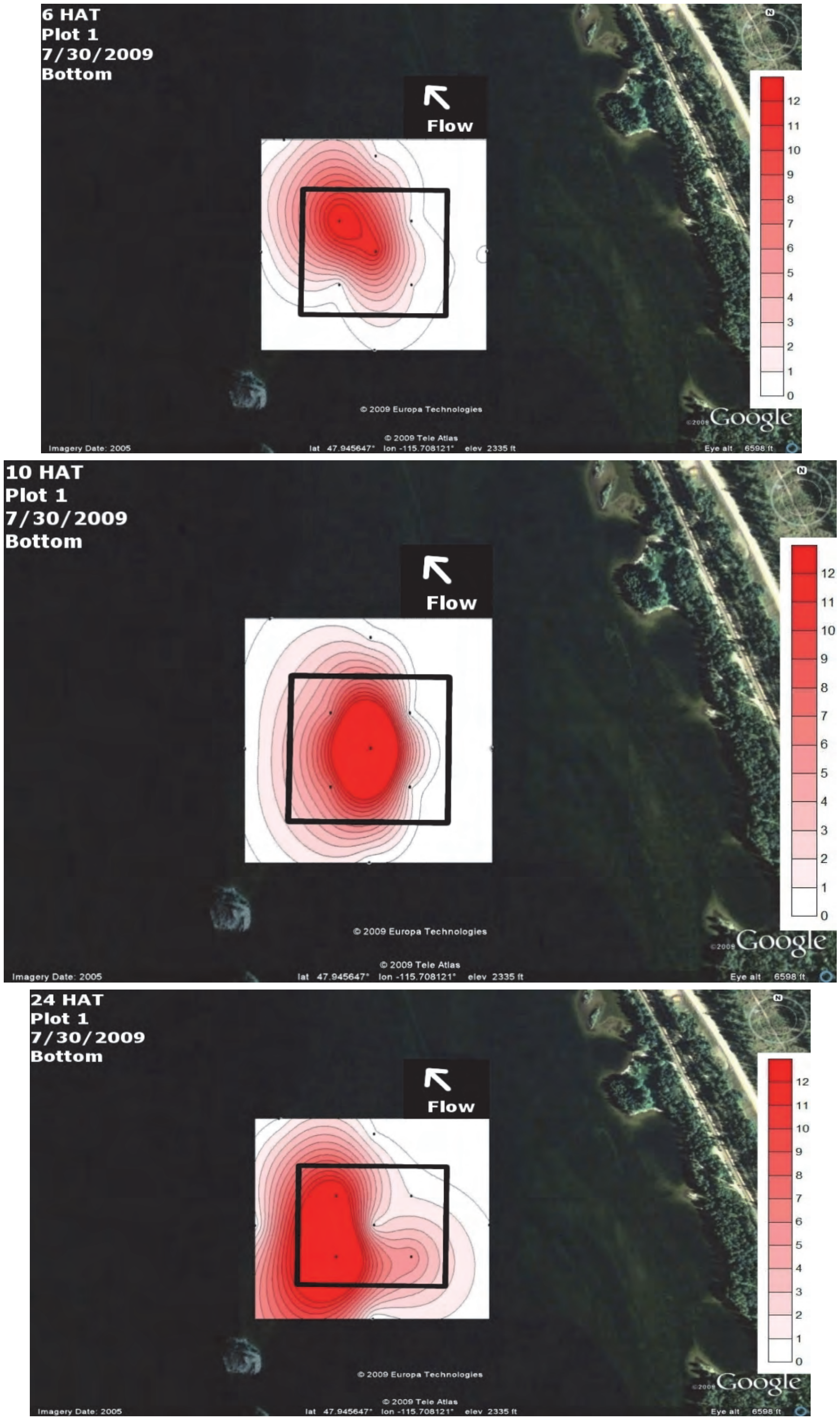

Figure 8. Dye dissipation pattern (µg/L) bottom depth zone, Plot 1 (dye + herbicide treatment) at 6, 10, and 24 hr after treatment, Noxon Rapids Reservoir, Montana, 30 July 2009.

Aqueous distribution of dye suggested that the variable-depth application technique successfully injected product into the lower portions of the water column. Through 33 HAT on the 22 July treatment, 30-55% was measured in the bottom zone and 55-80% at the mid + bottom zone (Figure 9), with the plot exhibiting a water-exchange half-life of 7 hr. However, on the 30 July application, which had a water exchange half-life of 33 hr, 30-60% was measured in the bottom zone for up to 68 HAT, and 60-85% at the mid + bottom zone for 68 hr (Figure 10). As demonstrated in Plot 1, placement of herbicides in and around target plant stands could be critical for achieving maximum efficacy.

Figure 11 depicts dye dissipation (simulating herbicide dissipation) in the bottom depth level at 1, 2.5, and 7 HAT. These patterns indicate that dye levels remained within the treated plot for moderate periods. This should translate into moderate herbicide exposure within the plot, resulting in adequate control of target weeds.

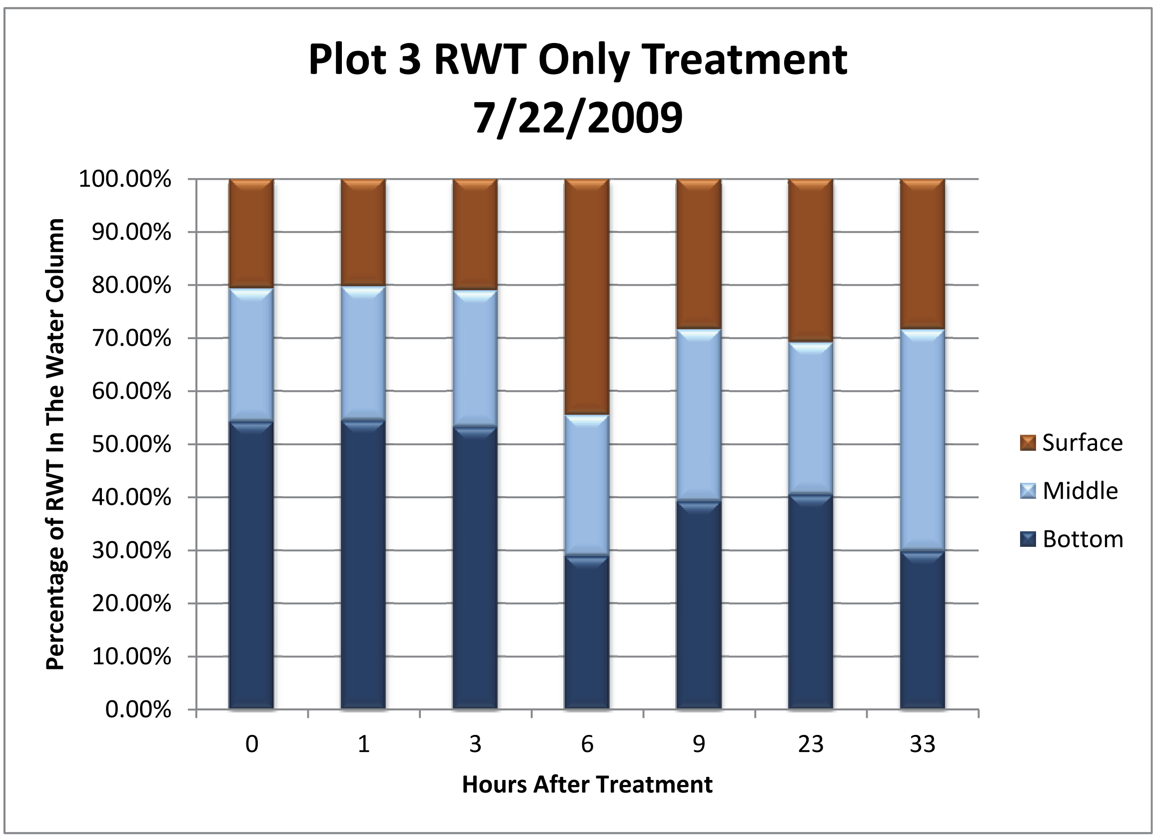

Figure 9. Water-column distribution of rhodamine WT (RWT) dye in Plot 3, Noxon Rapids Reservoir, Montana, 22 July 2009.

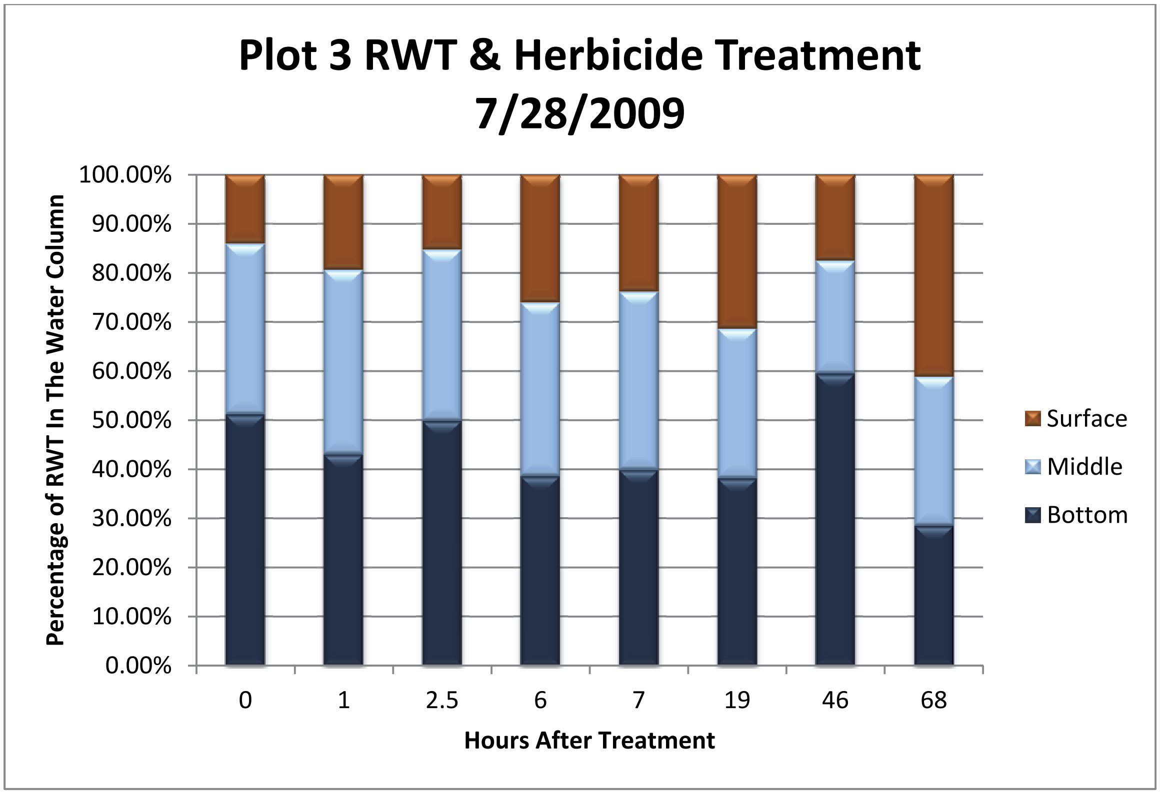

Figure 10. Water-column distribution of rhodamine WT (RWT) dye in Plot 3, Noxon Rapids Reservoir, Montana, 28 July 2009.

Conclusions and recommendations

Conclusions

The following conclusions can be reached on the basis of the research reported herein:

- Daily reservoir discharge patterns can influence bulk water exchange processes within submersed plant stands.
- At periods of low reservoir discharge, reduced bulk water exchange processes should provide adequate periods of herbicide contact time to control submersed invasive plants using combinations of triclopyr and endothall in treatment blocks $\geq$ 6 ha (15 acres) in size.
- Injection of dye with variable-depth application techniques demonstrated the potential to place herbicides in lower levels of the water column. This type of precision application technique could increase herbicide contact time around target plants growing in lower depth zones. In this way, plant stands are treated directly rather than treating the entire water column. This approach would potentially improve control while allowing for the use of reduced levels of herbicides.

Figure 11. Dye dissipation pattern (µg/L) at bottom depth zone, Plot 3 (dye + herbicide treatment) at 1, 2.5, and 7 hr after treatment, Noxon Rapids Reservoir, Montana, 28 July 2009.

Recommendations

The following recommendations are made on the basis of the research reported herein:

- Bulk water exchange processes should be evaluated in larger blocks of submersed plants (> 8 ha), and narrow shoreline treatment strips (< 2 ha) at various reservoir discharge patterns to determine the potential of chemical control in those situations.
- Results of such water exchange evaluations could warrant further evaluation of herbicide treatments in selected areas of the reservoir.

4 Herbicide Residues Following Treatments of Submersed Plant Stands Using Combinations of Endothall and Triclopyr

Objectives

The primary objective of this portion of the work was to characterize the dissipation of aqueous herbicide residues in stands of submersed plants, following treatments with combinations of endothall and triclopyr. Once determined, this information can be used to develop prescriptive herbicide application techniques (dose and product delivery) to maximize the species-selective control of invasive plants such as Eurasian watemilfoil and curlyleaf pondweed.

A secondary objective was to utilize aqueous herbicide residue data, driven by reservoir operations and discharge patterns, to verify CET relationships against target and non-target plants, both within and outside of treatment plots. This information can be used to design chemical applications that will maximize efficacy on target plants, and minimize impacts to areas outside of treatment zones–including potential contamination of potable water intakes and damage to environmentally sensitive areas.

Material and methods

Study site and plot descriptions

In mid-July 2009, four plots (8.2-11.5 ha in size) were selected for water-exchange and herbicide evaluations on Noxon Rapids Reservoir (Figure 1). All of the plots selected for these evaluations were located on Avista Utilities property. Plots 1 (8.2 ha) and 3 (7.7 ha) were selected for dye plus herbicide treatments, and Plots 2 (7.7 ha) and 4 (11.5 ha) were designated as reference or control plots. These plots were typical examples of littoral zones occurring in the reservoir that support submersed plant stands dominated by the invasive Eurasian watermilfoil. The plots also contained mixed populations of up to 14 other species of submersed plants including the invasive curlyleaf pondweed (see Chapter 3). Since dye and herbicides were not applied to the reference plots (Plots 2 and 4), this section of the report will only cover details pertaining to the treatment plots (Plots 1 and 3). Given that the treatment plots were situated in areas of differing

proximity to shorelines, open-water expanses, and deep-water drop-offs, an opportunity was provided to compare the efficacy, selectivity, and dissipation of the herbicides under varying water exchange and CET conditions that were imposed by the respective plot locations. Detailed plot descriptions are provided in Chapter 2.

Plot treatments - dye and herbicides

Bulk water-exchange processes were measured during the herbicide applications using the inert tracer dye, RWT. The liquid RWT dye was applied as a tank mix with water (or water plus herbicide) using a variable-depth injection system (LittLine®, CleanLakes, Inc., Coeur d'Alene, Idaho). To avoid product compatibility issues, dye was tank mixed with endothall only. The variable-depth application process simulated an operational liquid aquatic herbicide application, with the injection system calibrated to deliver product to the depth zone containing the targeted submersed plants (i.e. lower portions of the water column).

The RWT was applied to achieve a nominal rate of 10 µg/L, or 0.05 L of concentrated dye per acre-foot, based on the water volume of each plot. Dye levels were measured using Turner Designs Model 10-005 fluorometers equipped with high-volume continuous flow systems. Reservoir water was circulated through the fluorometers with submersible pumps attached to weighted opaque hoses, and pumps were positioned at selected sampling depths.

Herbicides consisted of the contact product, endothall (Aquathol® K, United Phosphorus, Inc.), and the systemic product, triclopyr (Kraken®, Phoenix Environmental Care). Both liquid formulations were applied using the LittLine® system (above) and at rates designed to achieve selective control of the target weeds, Eurasian watermilfoil and curlyleaf pondweed. These nominal rates were 1850 µg/L (1.85 ppm) triclopyr and 2500 µg/L (2.5 ppm) endothall in Plot 1, and 1300 µg/L (1.3 ppm) triclopyr and 1890 µg/L (1.89 ppm) endothall in Plot 3. Selected application rates were based upon results of the initial water-exchange evaluations (Chapter 2) and previously developed herbicide CET relationships for endothall and triclopyr against the target plants (Netherland et al. 1991; Netherland and Getsinger 1992; Getsinger et al. 1997; Poovey et al. 2002, 2004; Skogerboe and Getsinger 2002).

Plot 1- Applications and sampling

On 30 July, Plot 1 was treated simultaneously with tank-mixed combinations of dye and herbicides as three separate applications (splits). Each treatment split was applied evenly over the entire plot during a 50-min period. The complete application process lasted approximately 4.5 hr, starting at 0200 hr and ending at 0622 hr. Of that time period, ~ 1 hr elapsed to re-supply dye and herbicides to the application boat between application splits. Wind was calm during the treatment periods.

Fifteen sampling stations were established for dye measurements and herbicide monitoring (Figure 2): five internal (stations 20, 21, 22, 23, 25), and 10 external (stations 26-35). Internal stations were selected to provide coverage of the whole plot. External stations were located 75 to 250 m away from plot boundaries. These stations were selected to track dye and herbicide movement outside of the plot, and were primarily focused on downstream locations. Dye was measured using the fluorometric technique described above, and water samples were simultaneously collected from the fluorometer pump discharge stream. These water residue samples were collected in wide-mouth, amber, HPDE plastic 60-ml bottles, then fixed with three drops of 34.5% muriatic acid to biologically stabilize the samples. Samples were stored chilled and in the dark until shipment to the analytical laboratory. Dye measurements and herbicide residue samples were collected in the water column at three depths: 0.3 m below the surface (S), mid-depth (M), and 0.3 m above the bottom (B) at each station. There were 10 post-treatment sampling events: immediately after the entire application process had been completed, denoted as 0 hr after treatment (HAT), and at 1, 3, 6, 8, 10, 12, 24, 33, and 48 HAT. This sampling regime yielded a total of 450 samples.

Plot 3- Applications and sampling

On 28 July, the plot was treated simultaneously with tank-mixed combinations of dye plus herbicides as two separate blocks (shallow and deep as described above). Treatments were applied evenly over each block, with each treatment lasting ~ 1 hr. A 45-min period elapsed to re-supply dye and herbicides to the application boat between block applications. Therefore, the complete application process lasted ~ 2.75 hr, starting at 1003 hr and ending at 1243 hr. Winds were calm during the application periods.

Sixteen sampling stations were established for dye measurements and herbicide monitoring (Figure 4): nine internal (stations 1-8, 15) and seven external (stations 9-14, 16). Internal stations were selected to provide coverage of the whole plot. External stations were located 80 to 585 m away from the plot boundaries. These stations were selected to track dye and herbicide movement outside of the plot, and were primarily focused on projected downstream locations. Dye and herbicide were measured at all stations in the water column at three depths: S, M, and B at each station, as described for Plot 1 above. There were eight post-treatment sampling events: 0, 1, 2.5, 6, 7, 19, 46, and 68 HAT. This sampling regime yielded a total of 384 samples.

Reservoir discharge patterns

The overriding water-exchange process that impacts aqueous herbicide dissipation and herbicide CET relationships in the reservoir is operational discharge patterns. An example of summertime daily reservoir operations and subsequent discharge patterns (23 July 2009) is shown in Figure 5. The discharge is essentially nil during early morning hours (0330–0830 hr), but accelerates rapidly from 0900–1100 hr (0 to 22,000 cfs). This large pull of water through the dam early in the day reflects the rapid increase in mid-morning power demand. Discharge levels off, but remains high (22,000-25,000 cfs) until 2200 hr, when a steep discharge decline begins.

In Plot 1, applications were conducted at 0200-0630 hr to coincide with the minimum reservoir discharge pattern. By treating during this slack water period, water-exchange processes would be greatly reduced, and potential herbicide CET relationships would be increased in targeted treatment areas. These increased CET relationships should improve herbicide efficacy against target plants. Because this slack-water period occurred after daylight hours, this unconventional treatment strategy required navigation, herbicide loading, and application capabilities for night-time (dark) operations.

In Plot 3, applications were conducted at 1000-1245 hr, following the period of accelerated discharge (i.e. when discharge rates were nearly constant), but during the period when discharge patterns were high. In contrast to the application period for Plot 3, water-exchange processes would be active under this treatment scenario, reducing herbicide CET relationships that could negatively impact herbicide efficacy.

Herbicide residue analysis

Water residue samples were frozen immediately upon receipt at the analytical laboratory (US Army Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi). At least 48 hr prior to analysis, samples were transferred to the refrigerator to thaw. Samples and analytical test kits were removed from the refrigerator at least 1 hr before analysis to ensure they were at room temperature.

The RaPID Assay® Endothall Test Kit and the RaPID Assay® Triclopyr Test Kit (Strategic Diagnostics Incorporated (SDIX), Newark, Delaware) were used to quantify endothall acid and triclopyr residues, respectively. Both kits utilize the principles of enzyme-linked immunosorbent assay (ELISA) to quantify residues. First, an aliquot of the sample was mixed with diluent for a total sample volume of 1 mL. Samples were commonly diluted at either a 10:1 or 20:1 concentration for endothall samples and diluted at a 500:1 concentration for triclopyr samples. An aliquot of each sample was added to disposable test tubes along with an enzyme conjugate, followed by the addition of paramagnetic particles. The herbicide and the herbicide conjugate compete for binding sites on the paramagnetic particles. The samples were incubated for either 20 (endothall) or 30 (triclopyr) minutes, after which a magnetic field was applied to the tubes. The magnetic field secured the paramagnetic particles to the side of the test tube, thus allowing for any unbound reagents to be decanted.

The presence of endothall or triclopyr was detected by adding the enzyme substrate (hydrogen peroxide) and chromogen (3,3’,5,5’ – tetramethyl-benzidine), thus generating a colored product. The solution was incubated for either 15 (endothall) or 20 (triclopyr) minutes and then halted with the addition of acid. The level of color development was inversely proportional to the concentration of either endothall or triclopyr in the water because the enzyme-conjugated herbicide analog competed with the unlabeled herbicide for antibody sites.

For both herbicides, the actual quantification was achieved by first producing a standard curve using standards provided with each test kit. One group of nine standards was analyzed with each set. Computer software furnished with the kit system provided a means of obtaining the curve and calculating results. The standard curve was constructed using linear regression after a log/logit transformation of the concentration and absorbance values, respectively. If the kit standards had lower than a

0.990 correlation, then the results were not deemed acceptable. All unknown samples were analyzed against standard curves. A new curve was constructed for each set of samples analyzed. Absorbance (450 nm) was measured in each tube using an RPA-I Photoanalyzer™ (SDIX). At least one sample was spiked with a known concentration of herbicide and the percent recovery was reported. If the percent recovery was outside of acceptable parameters as deemed by the test kit procedures, then the test was repeated. Percentage error ranges and averages for all stations are presented in Table 2.

Table 2. Percentage error range and average for herbicide residue analyses for all stations within and outside of Plots 1 and 3 in Noxon Rapids Reservoir, Montana, July 2009.

Plot	Area	Herbicide	Percentage Error Range	Percent Error Average
1	Internal	Triclopyr	1.0 - 21.0	2.1
3	Internal	Triclopyr	5.4 - 37.0	2.2
1	Internal	Endothall	2.1 - 9.5	4.4
3	Internal	Endothall	0.3 - 12.3	3.2
1	External	Triclopyr	1.5 - 10.1	0.1
3	External	Triclopyr	0.5 - 23.0	1.8
1	External	Endothall	0.5 - 12.6	2.7
3	External	Endothall	0.5 - 12.3	2.8

Data analysis

Water exchange (dye) and herbicide half lives for all treated plots were determined using Sigma Plot 9.0, and subjected to a regression analysis using a sigmoid function.

Using this information, figures depicting aqueous herbicide averages were created for each plot. Separate figures were created for those stations that were considered within the direct treatment boundaries (Plot 1: Stations 20, 21, 22, 23, 25; Plot 3: Stations 1-8, 15) or outside of the boundaries (Plot 1: Stations 26-35; Plot 3: Stations 9-14, 16). Additional figures were created for stations within the treatment boundary to illustrate water column averages.

Results and discussion

Plot 1 - Triclopyr dissipation patterns

Inside Plot 1 - Internal sampling stations

Figure 12 depicts aqueous triclopyr and RWT dye concentration patterns measured within Plot 1 from 0 to 48 HAT. During this time period, mean±SE triclopyr concentrations ranged from 214±27 to 1244±36 µg/L, with most sampling events showing levels between 500 and 1000 µg/L, 27 to 54% of the nominal application rate of 1850 µg/L (Table 3). In addition, triclopyr residue patterns were similar to those exhibited by the dye. Previous studies have shown a strong correlation between triclopyr and RWT dissipation when applied simultaneously to surface waters (Getsinger et al. 1997, Fox et al. 2002).

When plotted against water column depth, mean triclopyr residues were 2.1 to 2.4 times higher in the bottom zone (1239±336 µg/L) than residues measured in the middle (582±92 µg/L) and surface (507±76 µg/L) zones (Figure 13, Table 4). This depth stratification of residues continued for the

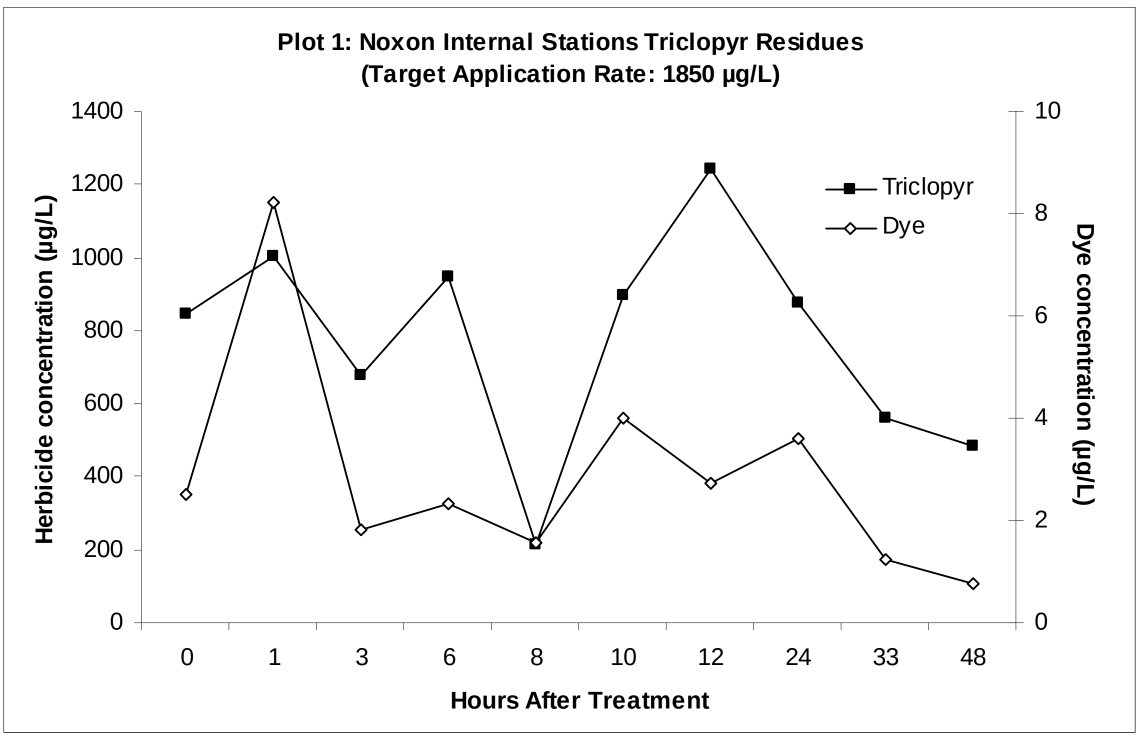

Figure 12. Average triclopyr concentration (µg/L) for internal stations 20, 21, 22, 23, and 25 within Plot 1. Also included is average dye concentration (µg/L) data for Plot 1. Study conducted on Noxon Rapids Reservoir, Montana, July 2009 (N = 15/HAT).

Table 3. Mean (±SE) for triclopyr and endothall herbicide concentrations (µg/L) determined for hours after treatment (HAT) within Plot 1 in Noxon Rapids Reservoir, Montana, July 2009.

HAT	Triclopyr	Endothall
0	847.35 +/- 8.81	1637.24 +/- 117.77
1	1001.33 +/- 34.44	2195.08 +/- 1042.70
3	676.67 +/- 43.77	406.83 +/- 47.05
6	948.83 +/- 21.78	1347.91 +/- 17.23
8	214.00 +/- 25.63	219.75 +/- 26.34
10	893.67 +/- 96.69	1460.19 +/- 31.84
12	1243.45 +/- 36.11	712.46 +/- 65.83
24	877.67 +/- 27.74	1111.16 +/- 8.92
33	560.71 +/- 55.53	233.52 +/- 15.41
48	481.43 +/- 95.23	163.75 +/- 78.35

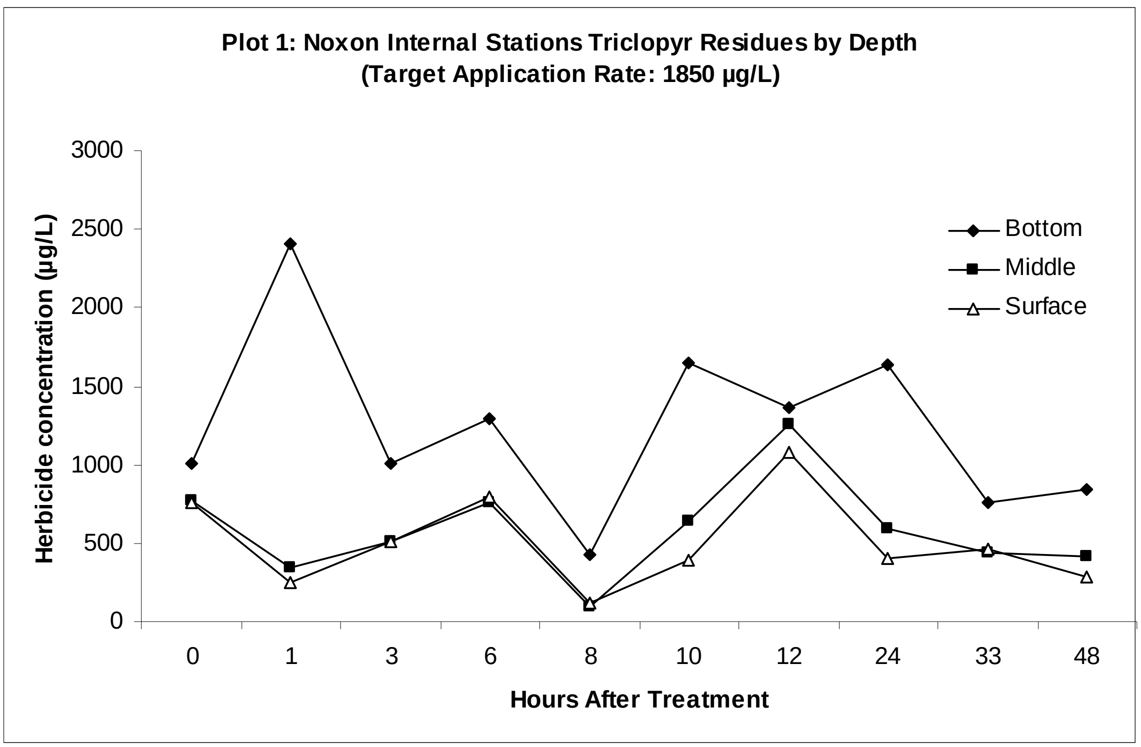

Figure 13. Average triclopyr concentration (µg/L) for internal stations 20, 21, 22, 23, and 25 within Plot 1, by depth. Study conducted on Noxon Rapids Reservoir, Montana, July 2009 (N = 5/depth/HAT).

Table 4. Mean (±SE) for triclopyr and endothall herbicide concentrations (µg/L) determined for hours after treatment (HAT) by depth (bottom, middle, surface) within Plot 1 in Noxon Rapids Reservoir, Montana, July 2009.

HAT	Triclopyr			Endothall		
	Bottom	Middle	Surface	Bottom	Middle	Surface
0	1011.81 +/- 393.37	770.63 +/- 95.53	759.62 +/- 15.25	2436.96 +/- 103.30	1293.78 +/- 122.72	1180.98 +/- 203.98
1	2410.00 +/- 343.48	345.00 +/- 79.20	249.00 +/- 59.65	3362.40 +/- 3010.94	1229.28 +/- 753.16	1993.56 +/- 1806.81
3	1010.00 +/- 275.94	505.00 +/- 66.84	515.00 +/- 75.81	646.70 +/- 242.16	258.64 +/- 60.08	315.16 +/- 81.49
6	1293.89 +/- 230.35	754.31 +/- 47.43	798.30 +/- 37.72	3848.40 +/- 2279.33	84.80 +/- 25.98	110.54 +/- 29.84
8	427.00 +/- 207.51	91.00 +/- 19.52	124.00 +/- 44.40	403.40 +/- 240.57	93.40 +/- 29.04	162.44 +/- 45.62
10	1646.00 +/- 461.48	643.00 +/- 305.71	392.00 +/- 167.46	3863.52 +/- 2509.61	395.88 +/- 209.54	121.16 +/- 55.16
12	1360.77 +/- 256.46	1261.75 +/- 138.47	1073.94 +/- 67.56	1338.84 +/- 1006.67	405.48 +/- 184.83	313.23 +/- 123.15
24	1632.00 +/- 413.25	592.00 +/- 47.21	409.00 +/- 48.05	3167.56 +/- 1519.67	70.92 +/- 16.83	95.00 +/- 15.45
33	760.00 +/- 319.68	441.00 +/- 90.86	461.25 +/- 103.89	513.44 +/- 404.16	83.21 +/- 21.70	71.52 +/- 28.84
48	837.50 +/- 457.50	412.50 +/- 27.50	290.00 +/- 145.46	121.05 +/- 67.75	191.50 +/- 171.60	173.70 +/- 119.69

sampling period, and mimicked the depth stratification pattern measured for RWT dye (Figure 7, above). The aqueous residue distribution pattern indicates that the variable-depth injection technique was applying most of the product into the lower depths of the treatment plot. As a result, water-column mixing of residues was still occurring during the sampling period, and herbicide rates would be highest around plant stands growing in the lower half of the water column for at least 48 hr.

Calculated half-lives for triclopyr in Plot 1 were 36 hr for surface, and >48 hr for middle, bottom, and whole plot (Table 5). Based on triclopyr CET relationships from previous work (Netherland and Getsinger 1992, Getsinger et al. 1997), the residue exposure period within the plot should provide adequate control of Eurasian watermilfoil. Auxin compounds, such as triclopyr, would typically not provide good control of monocots, such as curlyleaf pondweed, when used alone at the application rates and exposure times reported in this study.

Table 5. Calculated water-exchange half-lives for plots treated with triclopyr and endothall herbicides in surface, middle, and bottom depth zones, and for whole-plots in Noxon Rapids Reservoir, Montana, July 2009.

				Half Life (h)			
Plot	Date	Treatment	Surface	Middle	Bottom	Whole Plot	Respective R^2
Plot 1	7/30/2009	Triclopyr	36	>48	>48	>48	0.41, 0.91, 0.40, 0.91
		Endothall	<1	32	32	32	0.03, 0.42, 0.81, 0.62
Plot 3	7/28/2009	Triclopyr	42	54	31	43	0.43, 0.20, 0.70, 0.50
		Endothall	15	18	18	18	0.47, 0.50, 0.48, 0.82

Outside Plot 1 - External sampling stations

Aqueous triclopyr and RWT dye concentration patterns measured in stations outside of Plot 1 from 0 to 24 HAT are shown in Figure 14. As with residue patterns within Plot 1, triclopyr residues outside of the plot were similar to dye dissipation patterns. During this time period, mean triclopyr concentrations ranged from 7±1 to 42±31 µg/L (Table 5), or 0.5 to 3% of the maximum concentration measured within the treatment plot. Several hydraulic factors accounted for low levels outside the plot residues. Bulk water exchange and mixing processes occurring within the plot (t ½ = 33 hr, Table 1, above) would dilute and transport residues away from the plot, as the treated water mixed with untreated water. And, the extremely large area and volume of untreated water surrounding the relatively small plot of treated water would further dilute triclopyr concentrations, as residues were continuing to move away from the plot.

External triclopyr residues generally peaked at 6 to 8 HAT. While there was little flow-induced water exchange in the plot until the dam gates were opened at 0900 hr, the higher residue levels (100-150 µg/L) were measured in stations that were downstream from the southern plot boundary (Figures 15 and 16). These low levels of triclopyr would not be expected to impact plant populations, including the targeted invasive species. In addition, the concentrations are well below the 400 µg/L limit set as a label restriction by the US Environmental Protection Agency (USEPA) for triclopyr levels at potable water intakes.

Plot 1 - Endothall dissipation patterns

Inside Plot 1 - Internal sampling stations

Figure 17 depicts aqueous endothall and RWT dye concentration patterns measured within Plot 1 from 0 to 48 HAT. During this time period, mean±SE endothall concentrations ranged from 164±78 to 2195±1043 µg/L, with most

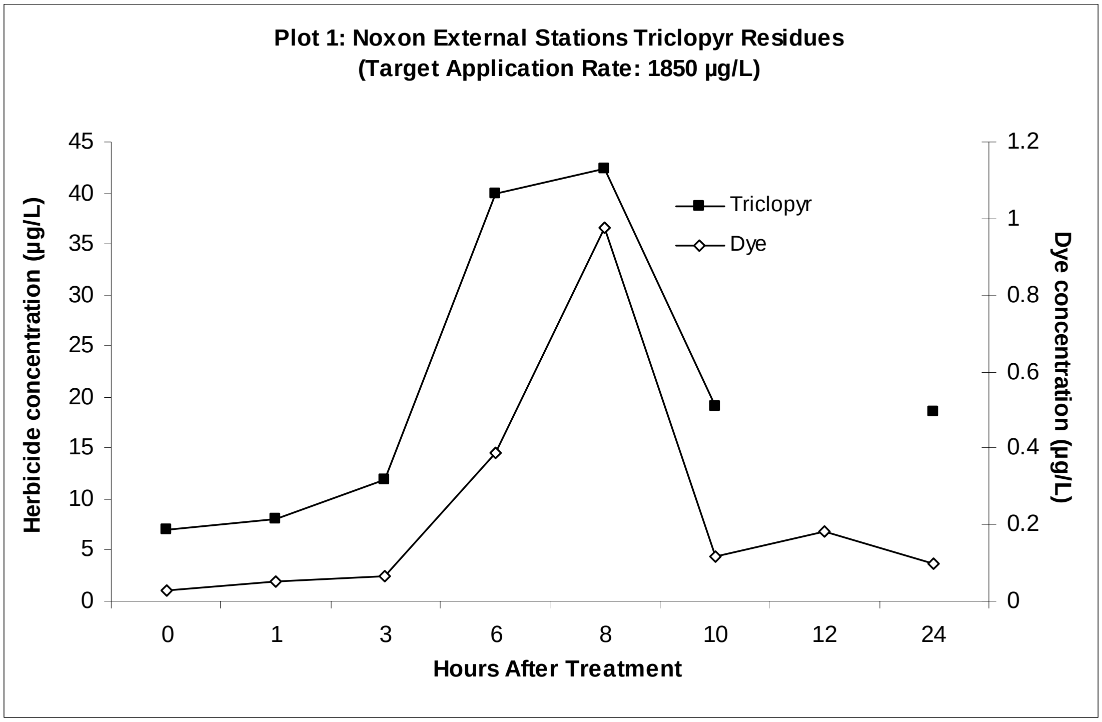

Figure 14. Average triclopyr concentration (µg/L) for external stations 26-35 outside of Plot 1. Average dye concentration (µg/L) data for Plot 1 are also included. Study conducted on Noxon Rapids Reservoir, Montana, July 2009.

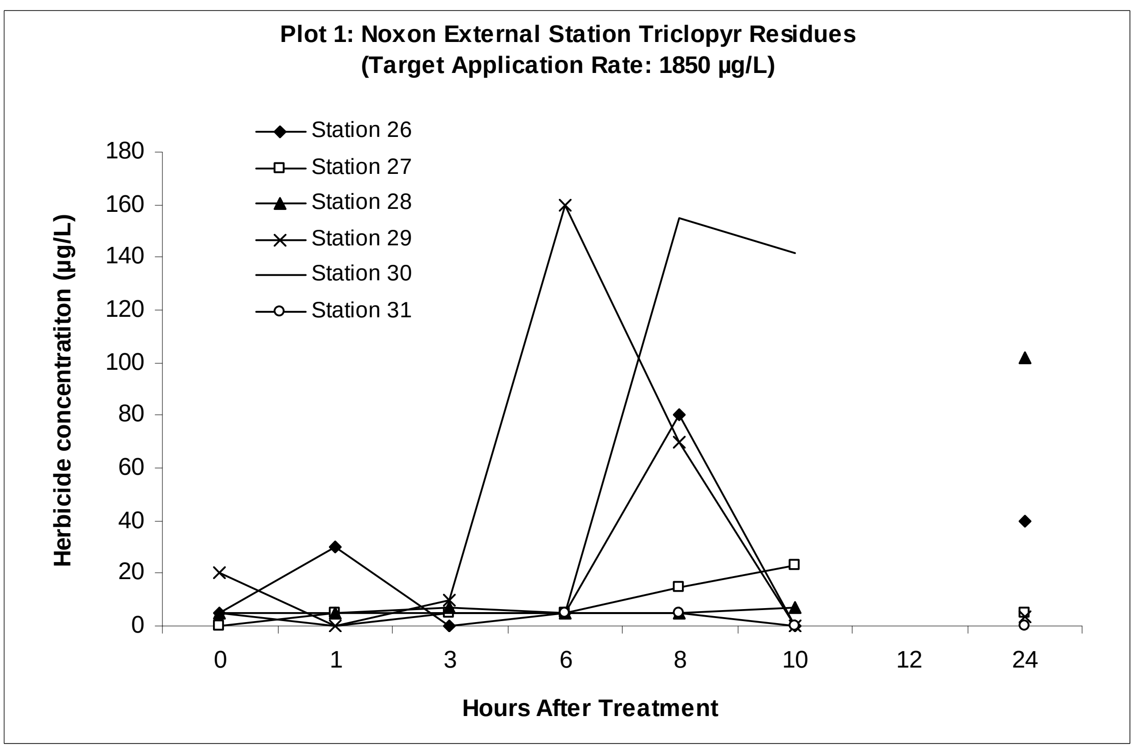

Figure 15. Average triclopyr concentration (µg/L) for external plot stations 26–31 outside of Plot 1, by station. Study conducted on Noxon Rapids Reservoir, Montana, July 2009. Note: No samples exist for 12 hr after treatment.

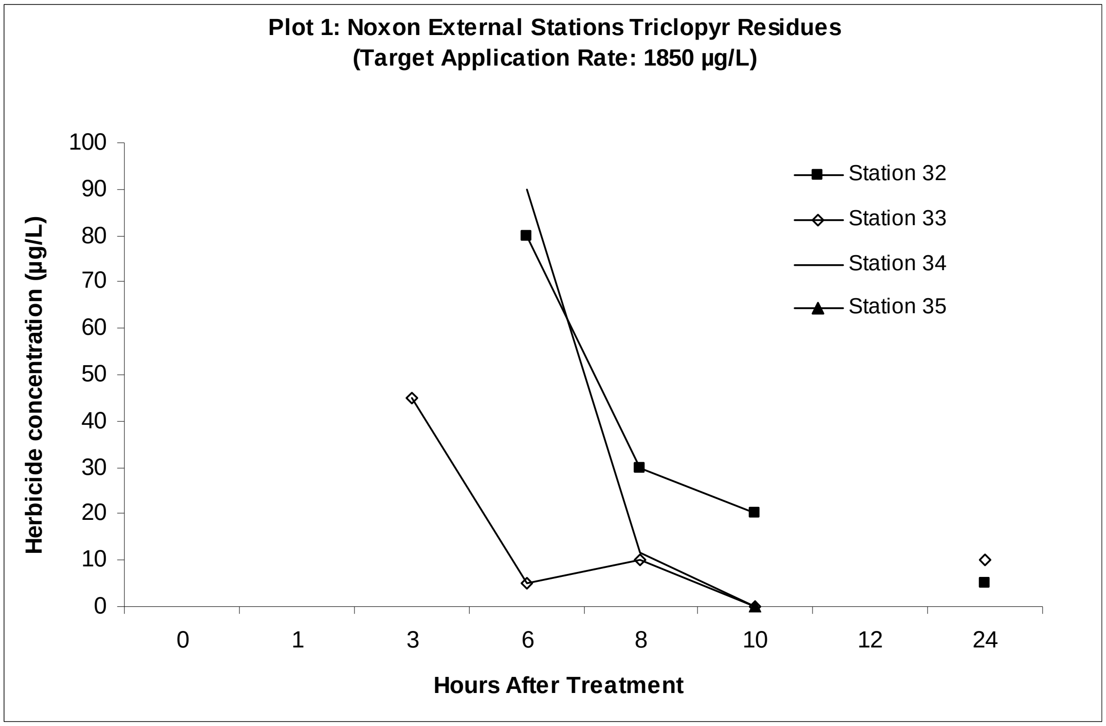

Figure 16. Average triclopyr concentration (µg/L) for external plot stations 32-35 outside of Plot 1, by station. Study conducted on Noxon Rapids Reservoir, Montana, 2009. Note: No samples exist for 12 hr after treatment.

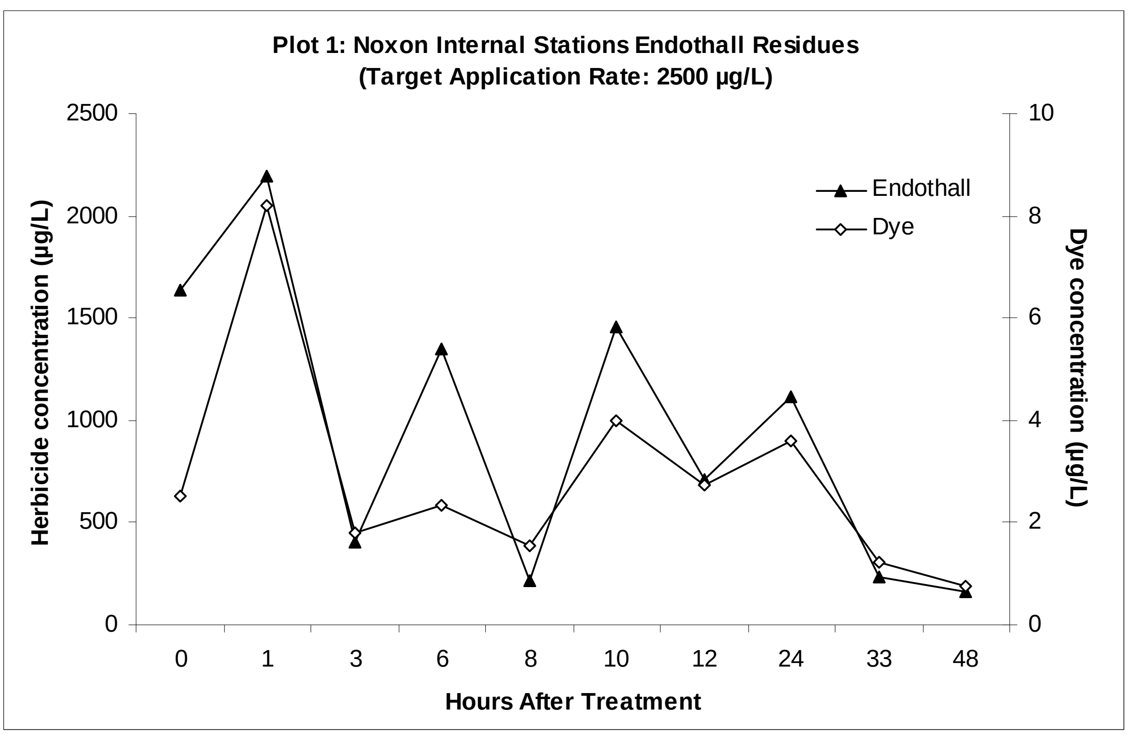

Figure 17. Average endothall concentration (µg/L) for internal stations 20, 21, 22, 23, and 25 within Plot 1. Average dye concentration (µg/L) data for Plot 1 are also included. Study conducted on Noxon Rapids Reservoir, Montana, July 2009 (N = 15/HAT).

sampling events showing levels between 400 and 1500 µg/L, which represents 16 to 60% of the nominal application rate of 2500 µg/L (Table 3). In addition, endothall residue patterns were similar to those exhibited by the dye. Previous work has shown a strong correlation between endothall and RWT dissipation when applied simultaneously to surface waters (Fox et al. 1993).

When plotted against water column depth, mean endothall residues were 4.8 times higher in the bottom zone (1970±1138 µg/L) than residues measured in the middle (411±160 µg/L) and surface (454±251 µg/L) zones (Figure 18; Table 4). This depth stratification of residues continued for the sampling period, and mimicked the depth stratification pattern measured for RWT dye (Figure 7, above). The aqueous residue distribution pattern indicates that the variable-depth injection technique applied most of the product into the lower depths of the treatment plot. As a result, water-column mixing of residues was still occurring during the sampling period, and herbicide rates would be highest around plant stands growing in the lower half of the water column for at least 48 hr.

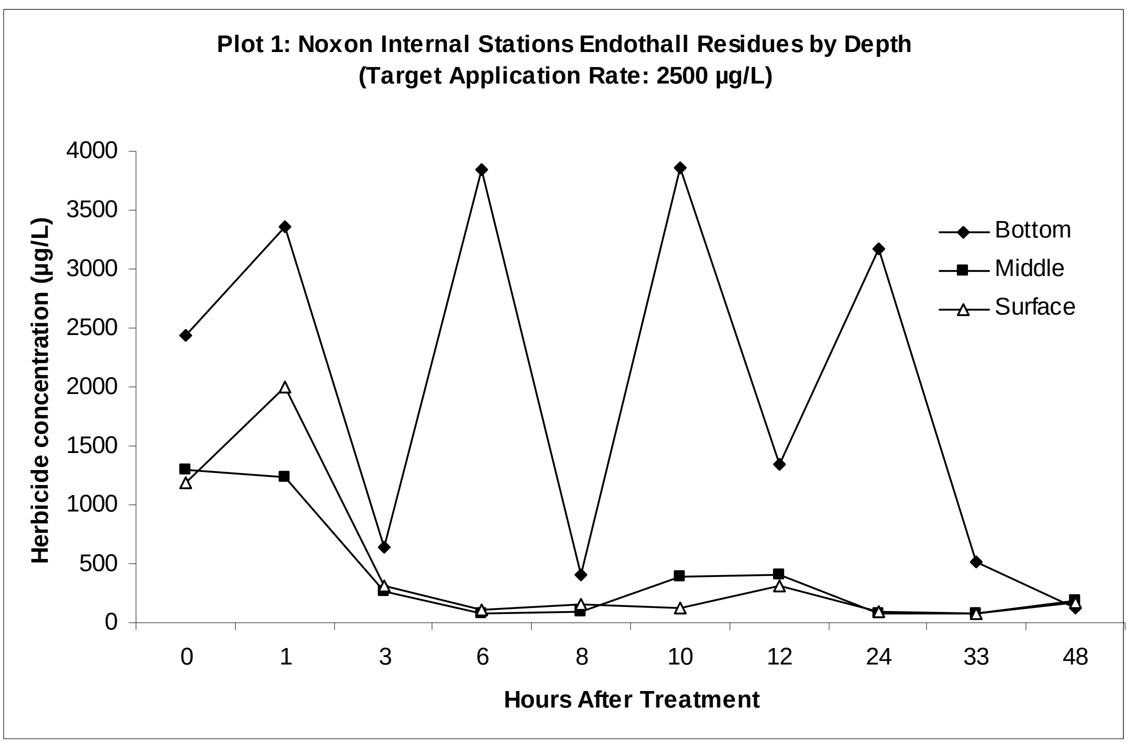

Figure 18. Average endothall concentration (µg/L) for internal stations 20, 21, 22, 23, and 25 within Plot 1, by depth. Study conducted on Noxon Rapids Reservoir, Montana, July 2009 (N = 5/depth/HAT).

Calculated half-lives for endothall in Plot 1 were <1 hr for surface and ~ 32 hr for middle, bottom, and whole plot (Table 5). Based on endothall CET relationships from previous work (Netherland et al. 1991, Skogerboe and Getsinger 2002, Madsen et al. 2010), the residue exposure period within the plot should provide fair to adequate control of Eurasian watermilfoil. However, the combination of endothall and triclopyr used in this study should improve efficacy on Eurasian watermilfoil (Madsen et al. 2010). While endothall rates used in this study have been shown to provide acceptable control of young curlyleaf pondweed in mesocosm and field evaluations (Skogerboe and Getsinger 2002, 2006, 2008, in preparation), the older growth stage of curlyleaf pondweed in this study may limit herbicide efficacy.

Outside Plot 1 - External sampling stations

Aqueous endothall and RWT dye concentration patterns measured in stations outside of Plot 1 from 0 to 24 HAT are shown in Figure 19. Endothall residues outside of the plot were somewhat similar to dye dissipation patterns. During this time period, mean endothall concentrations ranged from 0 to 614±6 µg/L, or 0 to 28% of the maximum concentration measured within the treatment plot (Table 5). Several hydraulic factors accounted for the low levels outside the plot residues. Bulk water exchange and mixing processes occurring within the plot (t ½ = 33 hr, Table 1, above) would dilute and transport residues away from the plot, as the treated water mixed with untreated water. And, the extremely large area and volume of untreated water surrounding the relatively small plot of treated water would further dilute triclopyr concentrations, as residues were continuing to move away from the plot.

External endothall residues generally peaked at 3 to 10 HAT. While there was little flow-induced water exchange in the plot until the dam gates were opened at 0900 hr, the higher residue levels (> 600 µg/L) were measured in stations that were downstream from the southern plot boundary (Figures 20 and 21). These lower levels of endothall would not be expected to impact plant populations, including the targeted invasive species.

Plot 3 - Triclopyr dissipation patterns

Inside Plot 3 - Internal sampling stations

Figure 22 depicts aqueous triclopyr and RWT dye concentration patterns measured within Plot 1 from 0 to 68 HAT. During this time period,

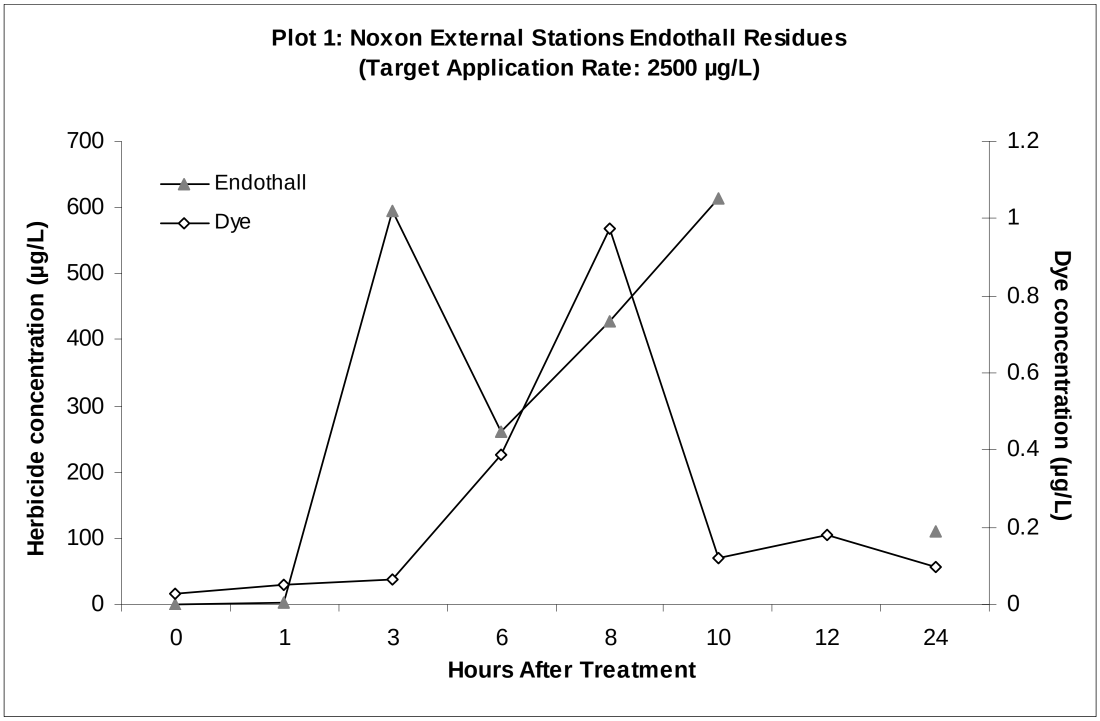

Figure 19. Average endothall concentration (µg/L) for external stations 26-35 outside of Plot 1. Average dye concentration (µg/L) data for Plot 1 are also included. Study conducted on Noxon Rapids Reservoir, Montana, July 2009.

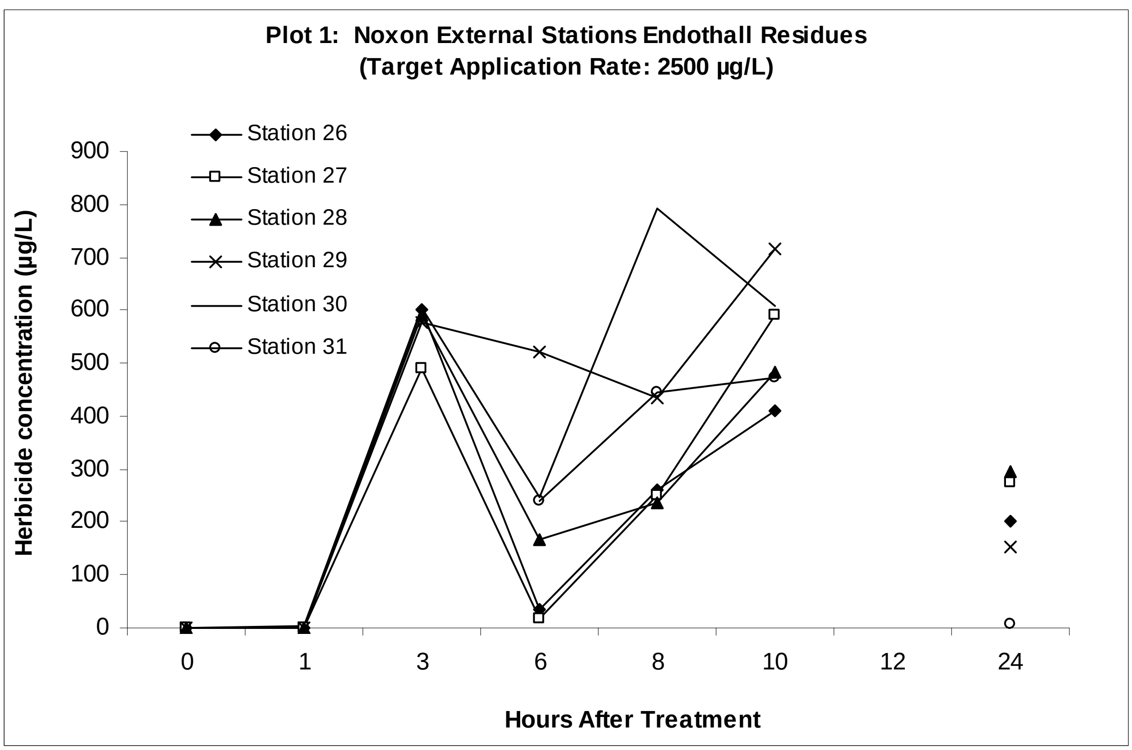

Figure 20. Average endothall concentration (µg/L) for external plot stations 26–31 outside of Plot 1, by station. Study conducted on Noxon Rapids Reservoir, Montana, July 2009. Note: No samples exist for 12 hr after treatment.

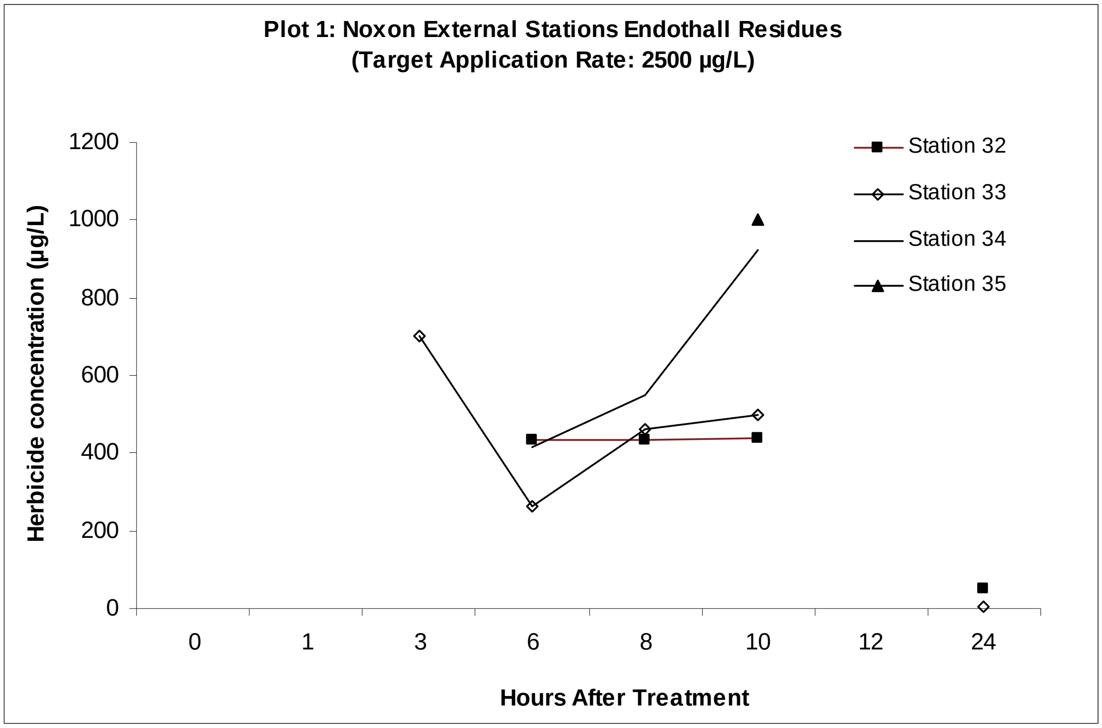

Figure 21. Average endothall concentration (µg/L) for external plot stations 32-35 outside of Plot 1, by station. Study conducted on Noxon Rapids Reservoir, Montana, July 2009. Note: No samples exist for 12 hr after treatment .

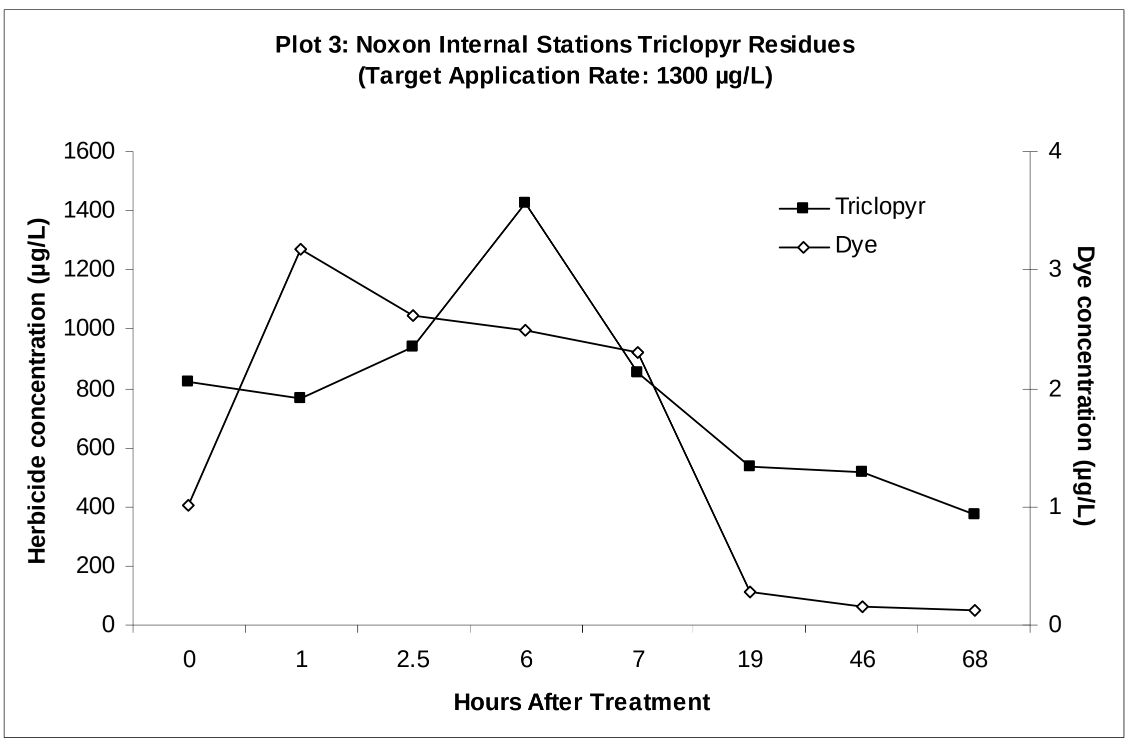

Figure 22. Average triclopyr concentration (µg/L) for internal stations 1-8 and 15 within Plot 3. Average dye concentration (µg/L) data for Plot 3 are also included. Study conducted on Noxon Rapids Reservoir, Montana, July 2009 (N = 25/HAT).

Table 6. Mean (+SE) for triclopyr and endothall herbicide concentrations (µg/L) determined for hours after treatment (HAT) outside of Plot 1, Noxon Rapids Reservoir, Montana, July 2009. No samples for 12 HAT.

HAT	Triclopyr	Endothall
0	7.00 +/- 1.33	0.00 +/- 0.00
1	8.00 +/- 28.98	2.72 +/- 2.27
3	11.94 +/- 19.04	593.72 +/- 14.84
6	40.00 +/- 14.43	259.86 +/- 33.99
8	42.41 +/- 30.86	428.82 +/- 47.97
10	19.17 +/- 10.28	614.37 +/- 5.70
12	N/A	N/A
24	18.52 +/- 8.45	110.45 +/- 40.01

mean+SE triclopyr concentrations ranged from 376+17 to 1423+222 µg/L, with most sampling events showing levels between 500 to 900 µg/L, 38 to 69% of the nominal application rate of 1300 µg/L (Table 7). As observed in the Plot 1 application, above, triclopyr residue patterns were similar to those exhibited by the dye.

Table 7. Mean (+ SE) for triclopyr and endothall herbicide concentrations (µg/L) determined for hours after treatment (HAT) within Plot 3 in Noxon Rapids Reservoir, Montana, July 2009.

HAT	Triclopyr	Endothall
0	823.67 +/- 111.39	1605.18 +/- 91.58
1	765.20 +/- 230.02	579.39 +/- 131.10
2.5	938.23 +/- 137.87	932.84 +/- 262.22
6	1423.43 +/- 222.09	986.24 +/- 371.92
7	853.40 +/- 259.43	1399.55 +/- 556.32
19	537.13 +/- 45.09	294.19 +/- 103.76
46	514.79 +/- 31.22	45.93 +/- 25.67
68	376.20 +/- 17.42	56.73 +/- 30.26

When plotted against water column depth, mean triclopyr residues were 1.5 times higher in the bottom zone (1015+248 µg/L) than residues measured in the middle (665+191 µg/L) and surface (659+197 µg/L) zones (Figure 23; Table 8). This depth stratification of residues continued for most of the sampling period, but was less pronounced by 19 HAT. Aqueous residues mimicked the depth stratification pattern measured for RWT dye

(Figure 8, above). While the proportion of product delivered to the bottom, versus mid to surface zones, was less than measured in Plot 1, it still indicates that the variable-depth injection technique applied most of the product into the lower depths of the treatment plot. As a result, water-column mixing of residues still occurred during much of the sampling period, and herbicide rates would be highest around plant stands growing in the lower half of the water column for at least 19 hr. The reduced delivery of product to the bottom in Plot 3 can likely be attributed to the higher flows (reservoir discharges) that occurred during and following the application process. By comparison, very limited flow occurred during and shortly after the application of products in Plot 1. This limited flow would tend to impede water column mixing processes. As a result, the potential to extend/enhance herbicide CET relationships exists when reservoir operations yield a reduction of bulk water exchange processes. An extension of CET relationships should lead to improved target plant control.

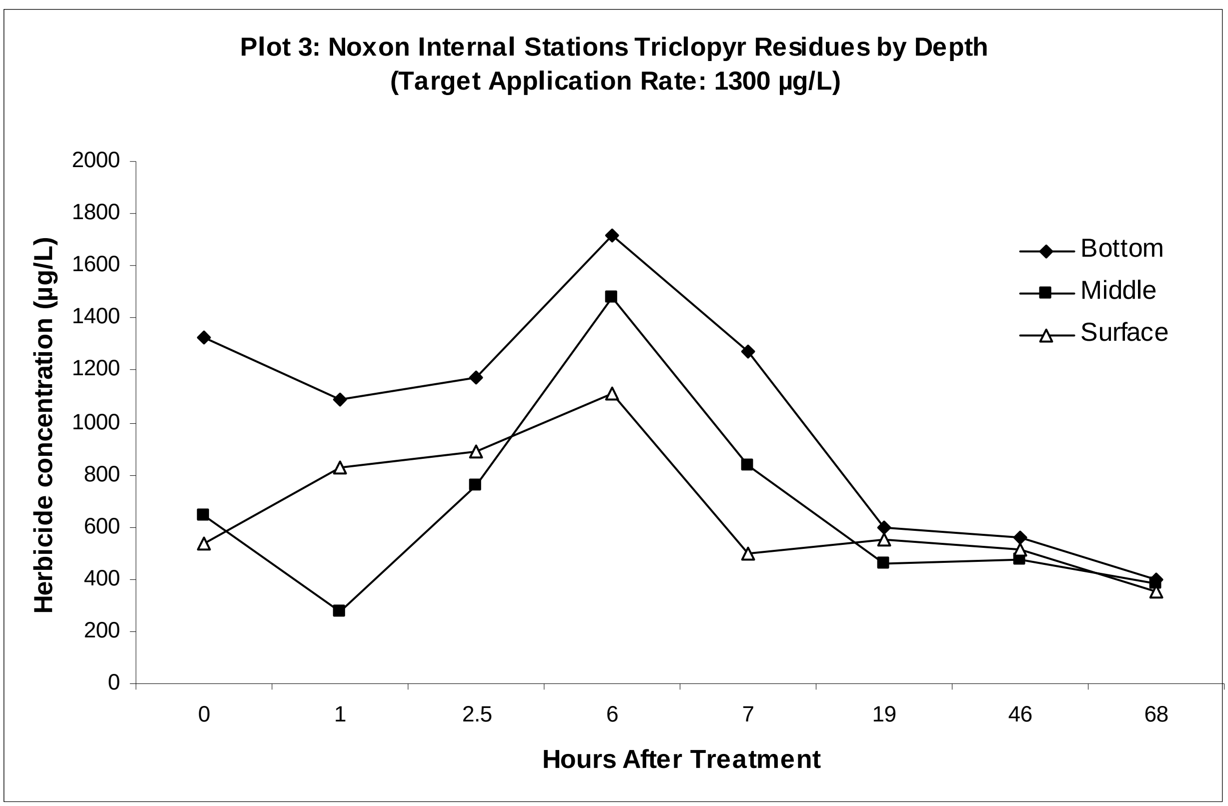

Figure 23. Average triclopyr concentration (µg/L) for internal stations 1-8 and 15 within Plot 3, by depth. Study conducted on Noxon Rapids Reservoir, Montana, July 2009 (N = 8 or 9 [station 15, surface]/depth/HAT).

Table 8. Mean ($\pm$SE) for triclopyr and endothall herbicide concentrations (µg/L) determined for hours after treatment (HAT) by depth (bottom, middle, surface) within Plot 3 in Noxon Rapids Reservoir, Montana, July 2009.

HAT	Triclopyr			Endothall		
	Bottom	Middle	Surface	Bottom	Middle	Surface
0	1327.42 +/- 218.95	646.39 +/- 133.62	533.47 +/- 100.08	1865.75 +/- 234.07	1533.13 +/- 86.27	1437.62 +/- 99.28
1	1086.67 +/- 346.72	272.86 +/- 129.65	826.67 +/- 538.65	737.08 +/- 162.22	289.10 +/- 113.99	647.49 +/- 319.52
2.5	1170.76 +/- 210.19	760.96 +/- 183.87	889.25 +/- 296.56	1198.08 +/- 343.37	594.35 +/- 358.98	997.94 +/- 599.97
6	1714.49 +/- 462.63	1481.72 +/- 470.67	1112.89 +/- 224.50	162.91 +/- 61.67	1690.11 +/- 889.09	1092.43 +/- 634.93
7	1271.88 +/- 591.60	836.25 +/- 512.20	496.67 +/- 221.88	1725.81 +/- 1092.35	1023.28 +/- 680.58	1444.02 +/- 1123.80
19	598.65 +/- 66.04	458.21 +/- 42.84	552.61 +/- 104.78	302.31 +/- 86.02	152.76 +/- 78.88	412.69 +/- 274.10
46	558.13 +/- 75.67	476.25 +/- 35.55	510.00 +/- 47.44	39.80 +/- 17.39	11.23 +/- 6.49	86.76 +/- 73.05
68	396.88 +/- 11.22	386.25 +/- 16.25	348.89 +/- 45.54	29.40 +/- 12.69	16.88 +/- 10.42	116.44 +/- 81.95

Calculated half-lives for triclopyr in S, M, and B depth zones, and within the whole plot, ranged from 31 to 54 hr (Table 5). Based on triclopyr CET relationships from previous work (Netherland and Getsinger 1992; Getsinger et al. 1997), the residue exposure period within the plot should provide adequate control of Eurasian watermilfoil. Auxin compounds, such as triclopyr, would typically not provide good control of monocots, such as curlyleaf pondweed, when used alone at application rates and exposure times reported in this study.

Outside Plot 3 - External sampling stations

Aqueous triclopyr and RWT dye concentration patterns measured in stations outside of Plot 3 from 0 to 68 HAT are shown in Figure 24. Unlike residue patterns within Plot 3, triclopyr residues outside of the plot did not track dye dissipation until 7 HAT. Mean triclopyr concentrations ranged from 0 to 63 ± 22 µg/L (Table 9), or 0 to 4% of the maximum concentration measured within the treatment plot. Several hydraulic factors accounted for low levels outside the plot residues. Bulk water exchange and mixing processes occurring within the plot ($t_{½}$ = 16 hr, Table 1, above) would dilute and transport residues away from the plot, as the treated water

mixed with untreated water. And, the extremely large area and volume of untreated water on the eastern and northern (downstream) boundaries of the relatively small plot of treated water would further dilute triclopyr concentrations, as residues were continuing to move away from the plot.

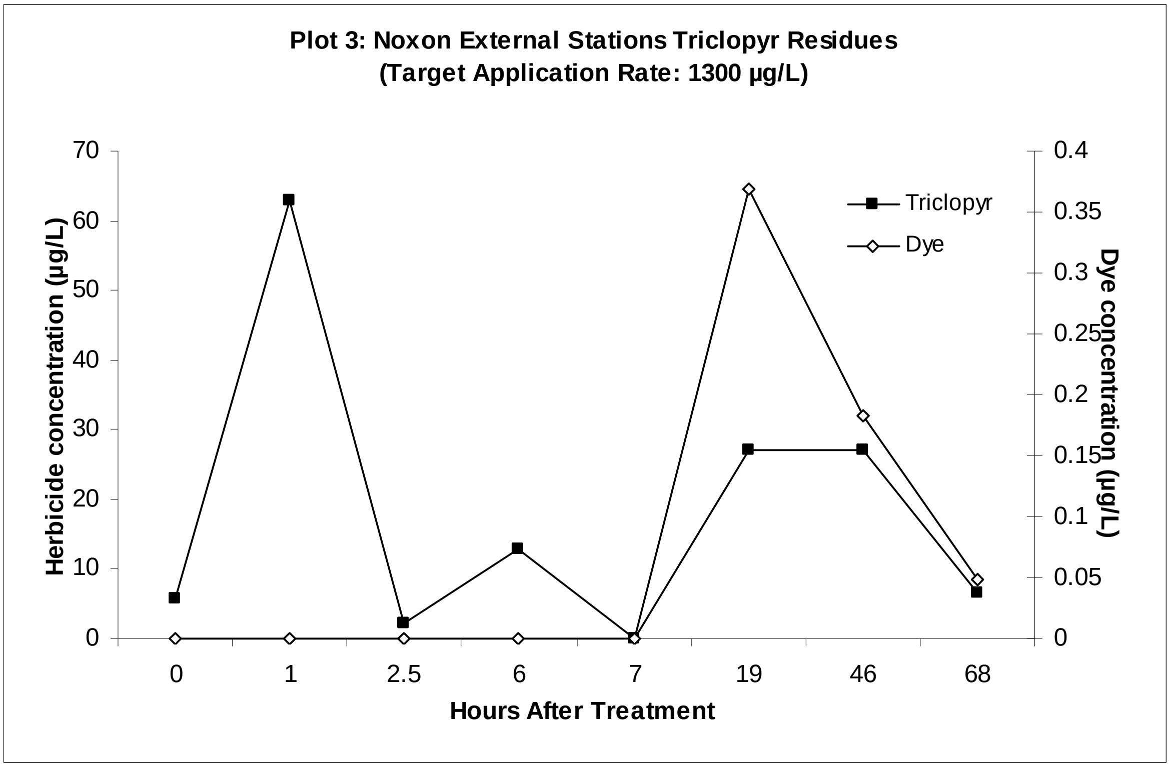

Figure 24. Average triclopyr concentration (µg/L) for external stations 9-14 and 16 outside of Plot 3. Average dye concentration (µg/L) data for Plot 3 are also included. Study conducted on Noxon Rapids Reservoir, Montana, July 2009.

Table 9. Mean (+SE) for triclopyr and endothall herbicide concentrations (µg/L) determined for hours after treatment (HAT) intervals outside of Plot 3 in Noxon Rapids Reservoir, Montana, July 2009.

HAT	Triclopyr	Endothall
0	5.63 +/- 3.07	169.89 +/- 63.31
1	62.92 +/- 22.10	2.33 +/- 1.21
2.5	2.08 +/- 2.08	176.27 +/- 75.48
6	12.83 +/- 9.15	5.72 +/- 1.95
7	0.00 +/- 0.00	22.43 +/- 7.89
19	27.17 +/- 6.64	8.28 +/- 3.39
46	27.14 +/- 10.57	34.03 +/- 9.00
68	6.58 +/- 21.63	15.15 +/- 4.64

External triclopyr residues generally peaked at 1 and > 19 HAT. Since the dam gates were open during and following application, there was considerable flow-induced water exchange in the plot, and the higher residue levels (60-180 µg/L) were measured in stations not far downstream from the southern plot boundary (Figure 25). Triclopyr residues were lower (< 40 µg/L) in downstream stations located further from the plot. These low levels of triclopyr would not be expected to impact plant populations, including the targeted invasive species. In addition, the concentrations are well below the 400 µg/L limit set as a label restriction by the USEPA for triclopyr levels at potable water intakes.

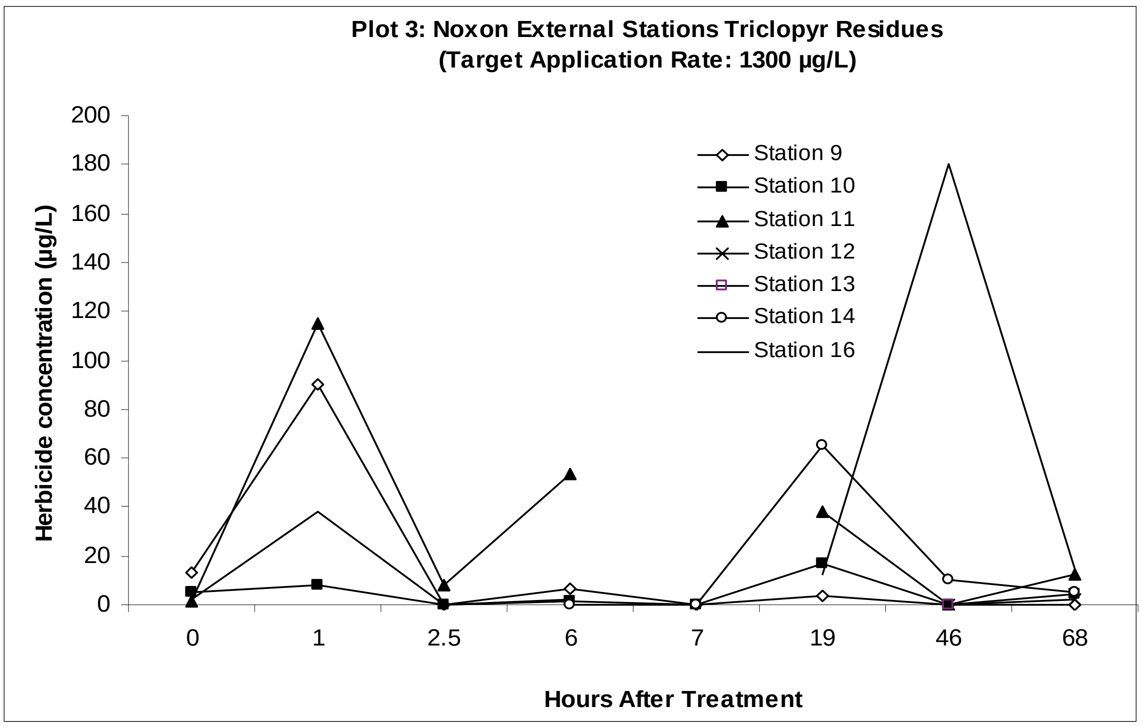

Figure 25. Average triclopyr concentration (µg/L) for external stations 9-14 and 16 outside of Plot 3, by station. Study conducted on Noxon Rapids Reservoir, Montana, July 2009.

Plot 3 - Endothall dissipation patterns

Inside Plot 3 - Internal sampling stations

Figure 26 depicts aqueous endothall and RWT dye concentration patterns measured within Plot 3 from 0 to 68 HAT. During this time period, mean ±SE endothall concentrations ranged from 46±26 to 1605±92 µg/L, with most sampling events showing levels between 500 and 1300 µg/L, 26 to 69% of the nominal application rate of 1890 µg/L (Table 7). In addition, endothall residue patterns were similar to those exhibited by the dye.

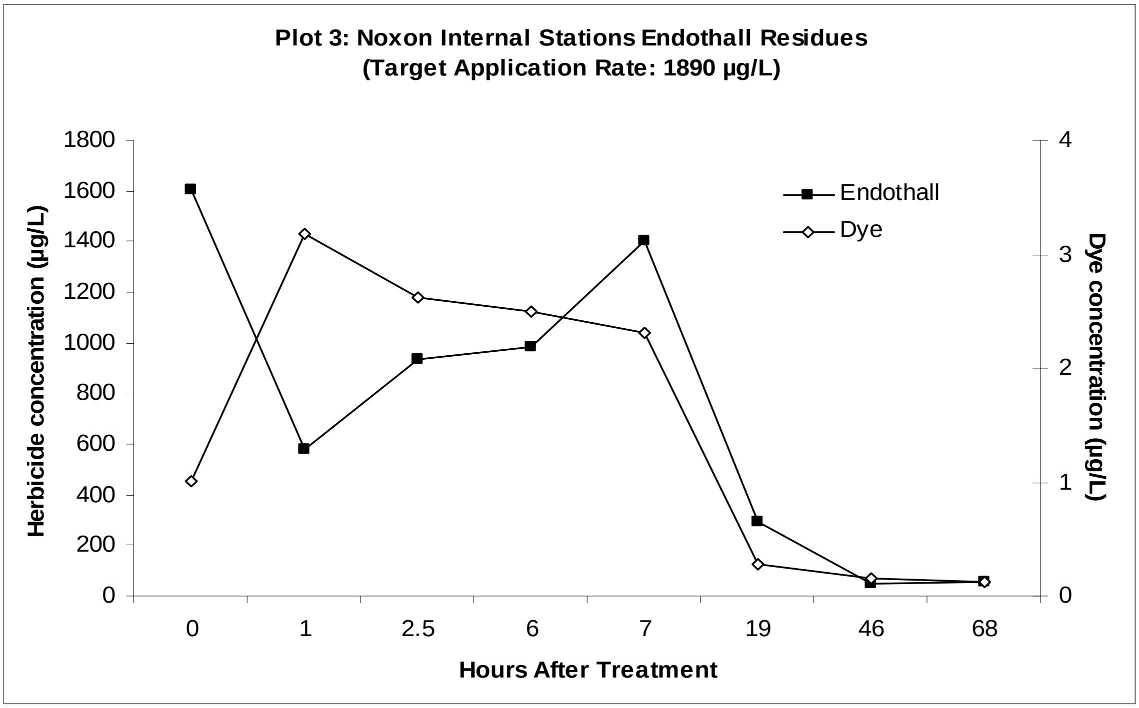

Figure 26. Average endothall concentration (µg/L) for internal stations 1-8 and 15 within Plot 3. Average dye concentration (µg/L) data for Plot 3 are also included. Study conducted on Noxon Rapids Reservoir, Montana, July 2009 (N = 25/HAT).

When plotted against water column depth, mean endothall residues were slightly higher in the bottom zone (758±251 µg/L) than residues measured in the middle (664±265 µg/L), and were similar to residues found in surface (767±401 µg/L) zones (Figure 27, Table 8).

Depth stratification of residues was not as pronounced as the sampling stratification pattern measured for RWT dye (Figure 9, above). While the proportion of endothall delivered to the water column was better mixed among depth zones than dye or triclopyr, the variable-depth injection technique was still applying most of the product into the lower depths of the treatment plot. As noted above for triclopyr, the reduced delivery of endothall to the bottom in Plot 3 can likely be attributed to the higher flows (reservoir discharges) that occurred during and following the application process. These water exchange patterns would enhance water column mixing in the plot. However, herbicide rates would be highest around plant stands growing in the lower half of the water column for at least 19 hr.

Calculated half-lives for endothall in Plot 3 were 15 hr for surface, and 18 hr for middle, bottom, and whole plot (Table 5). Based on endothall CET relationships from previous work (Netherland et al. 1991; Skogerboe and

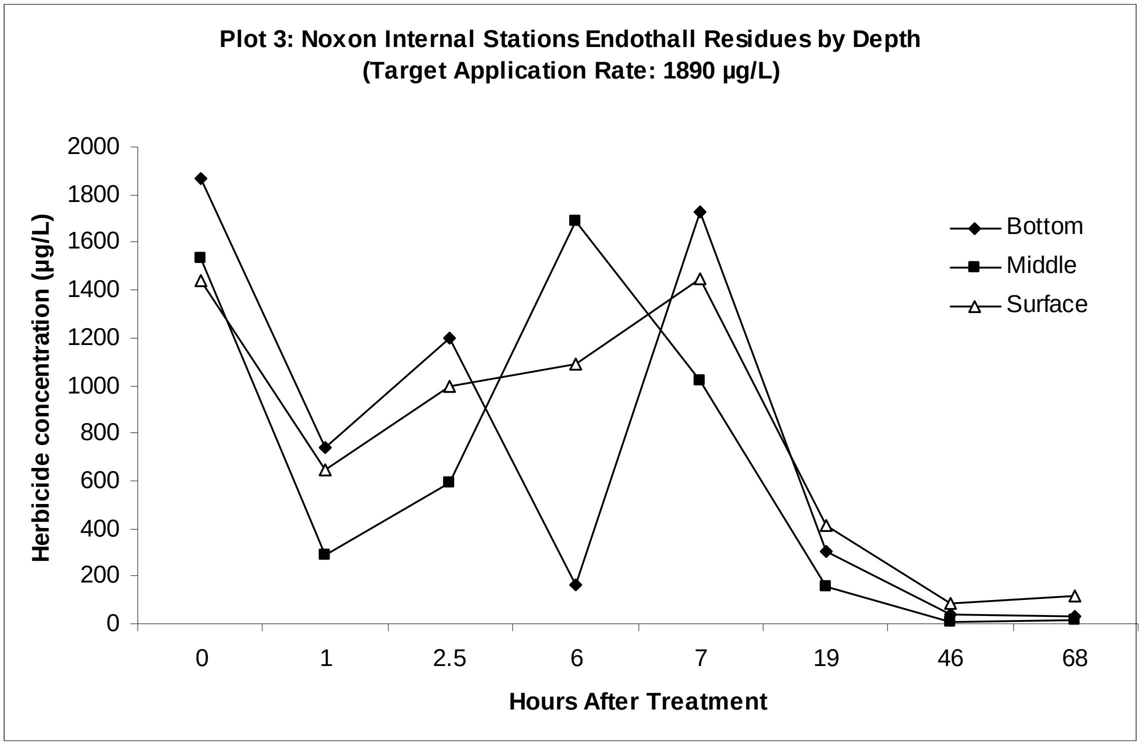

Figure 27. Average endothall concentration (µg/L) for internal stations 1-8 and 15 within Plot 3, by depth. Study conducted on Noxon Rapids Reservoir, Montana, July 2009 (N = 8 or 9 [station 15, surface]/depth/HAT).

Getsinger 2002; Madsen et al. 2010), the residue exposure period within the plot should provide fair to adequate control of Eurasian watermilfoil. However, the combination of endothall and triclopyr used in this study should improve efficacy against Eurasian watermilfoil (Madsen et al. 2010). While endothall rates in this study have been shown to provide acceptable control of young curlyleaf pondweed in mesocosm and field evaluations (Skogerboe and Getsinger 2002, 2006, 2008; Skogerboe et al. 2012), the older growth stage of curlyleaf pondweed during this application may limit herbicide efficacy.

Outside Plot 3 - External sampling stations

Aqueous endothall and RWT dye concentration patterns measured in stations outside of Plot 3 from 0 to 68 HAT are shown in Figure 28. Endothall residues outside of the plot did not mimic dye dissipation patterns. During this time period, mean endothall concentrations ranged from 2±1 to 176±75 µg/L (Table 9), or <1 to 11% of the maximum concentration measured within the treatment plot. Several hydraulic factors accounted for the low levels outside the plot residues. Bulk water exchange and mixing

processes occurring within the plot (t ½ = 16 hr, Table 1, above) would dilute and transport residues away from the plot, as the treated water mixed with untreated water. The extremely large area and volume of untreated water on the eastern and northern (downstream) boundaries of the relatively small plot of treated water would further dilute endothall concentrations, as residues were continuing to move away from the plot.

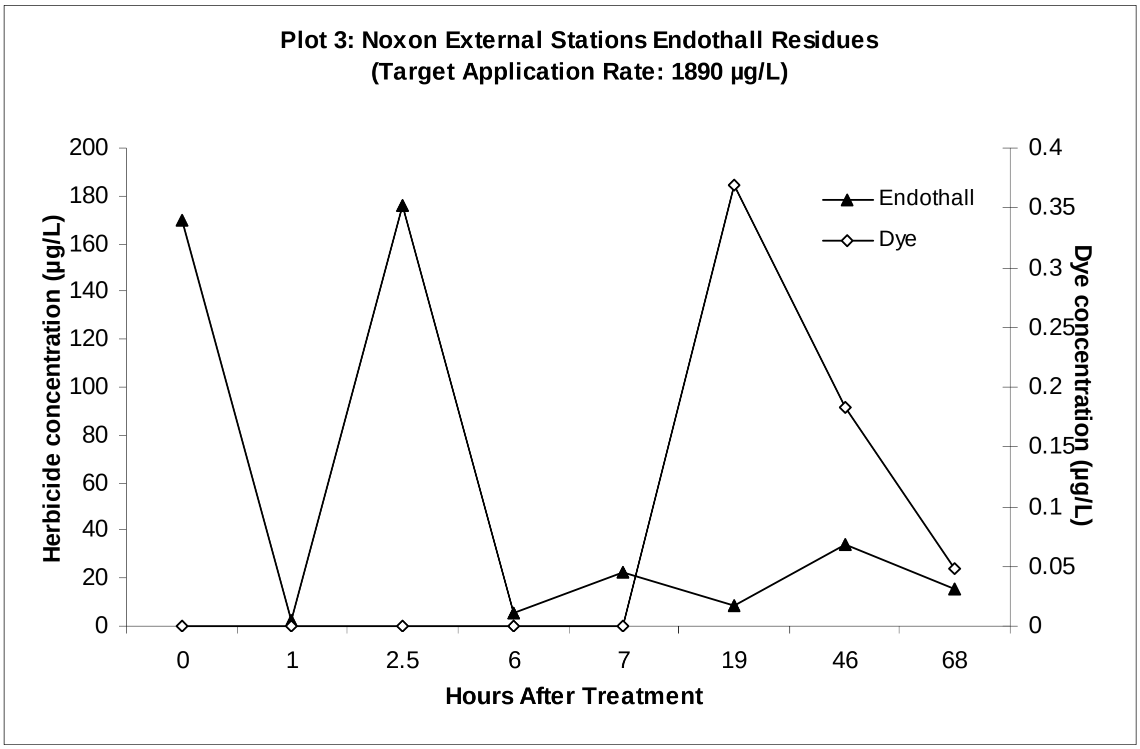

Figure 28. Average endothall concentration (µg/L) for external stations 9-14 and 16 outside of Plot 3. Average dye concentration (µg/L) data for Plot 3 are also included. Study conducted on Noxon Rapids Reservoir, Montana, July 2009.

External endothall residues generally peaked at 2.5 HAT, with a slight downstream peak of 140 µg/L at 46 HAT. Since the dam gates were open during and following application, there was considerable flow-induced water exchange in the plot, and the higher residue levels (200-350 µg/L) were measured in stations not far downstream from the southern plot boundary (Figure 29). Endothall residues were lower (< 50 µg/L) in downstream stations located further from the plot. These low levels of endothall would not be expected to impact plant populations, including the targeted invasive species.

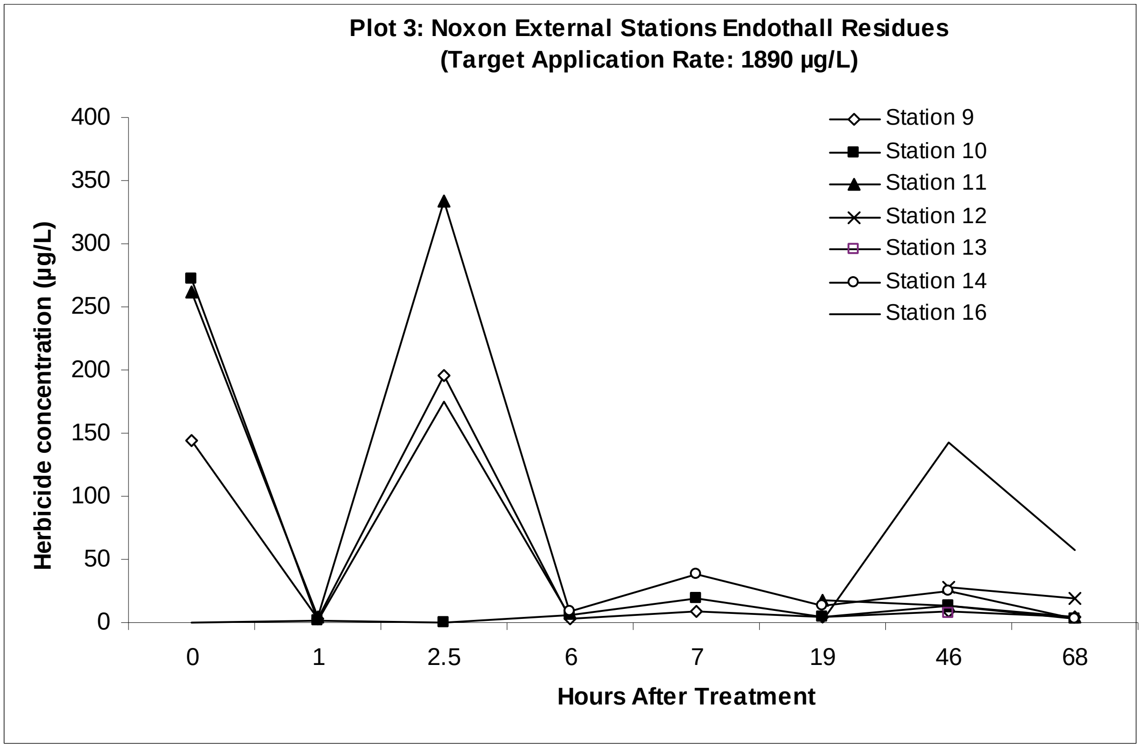

Figure 29. Average endothall concentration (µg/L) for external stations 9-14 and 16 outside of Plot 3, by station. Study conducted on Noxon Rapids Reservoir, Montana, July 2009.

Conclusions and recommendations

Conclusions

The following conclusions were reached on the basis of the research conducted in this study:

- Since daily reservoir discharge patterns can impact bulk water exchange processes within submersed plant stands, these same processes can influence dissipation of aqueous herbicide residues, both within and outside of treated plots.
- At periods of low reservoir discharge, water exchange processes are limited, enhancing herbicide exposure periods within treatment areas. Longer exposure periods for herbicides will improve control of invasive plants, e.g. Eurasian watermilfoil and curlyleaf pondweed, in plant stands $\geq$ 6 ha (15 acres) in size.
- Dissipation of herbicides within, and outside of, treated plots was relatively short. Residue levels outside of plots did not impact off-site vegetation and fell within water use restrictions on product labels.
- Variable-depth injection application techniques placed products in lower levels of the water column. This precision application approach

should enhance herbicide concentration and exposure time relationships around target plants, thereby improving efficacy.
- The precision placement of herbicides around target plant stands has the potential to allow for reduced levels of herbicides to be used (38–74% of maximum label rates in this study), because plant stands are treated directly rather than treating the entire water column. Reducing herbicide use can equate to lower environmental pesticide loading, cost savings, and reduced handling of pesticides by applicators.

Recommendations

- Herbicide applications should be evaluated in larger blocks of submersed plants (> 8 ha), and narrow shoreline strips (< 2 ha) at various reservoir discharge patterns to determine the potential of chemical control in those situations.
- Evaluations should be conducted to refine herbicide use rates when utilizing variable depth application techniques. Maintaining herbicides in bottom waters, where young invasive plants are growing, may provide improved control, allow for less herbicide to be used, and reduce treatment costs.

5 Pre- and Post-treatment Vegetation Assessment Following Herbicide Applications in Noxon Rapids Reservoir

Introduction

Aquatic plants are important to lake ecosystems (Madsen et al. 1996, Wetzel 2001) and are essential in promoting the diversity and function of an aquatic system (Carpenter and Lodge 1986). Littoral zone habitat and associated plants may be responsible for a significant proportion of primary production for the entire lake (Ozimek et al. 1990, Wetzel 2001). Littoral zone habitats are prime areas for the spawning of most fish species, including many species important to sport fisheries (Savino and Stein 1989). Furthermore, aquatic plants anchor soft sediments, stabilize underwater slopes, remove suspended particles, and remove nutrients from overlying waters (Barko et al. 1986, Doyle 2000, Madsen et al. 2001). However, when non-native plants invade littoral zone habitat, changes in biotic and abiotic interactions often occur (Madsen 1998). The growth of non-native species often results in reductions in littoral zone plant species, resulting in decreases in fish production (Savino and Stein 1989), increases in sediment resuspension, turbidity, and algal production; the latter will further exacerbate plant loss (Madsen et al. 1996, Doyle 2000, Case and Madsen 2004, Wersal et al. 2006).

Eurasian watermilfoil is an invasive vascular plant that has invaded freshwater lakes across the United States. The introduction of Eurasian watermilfoil has likely resulted in the alteration of the complex interactions occurring in littoral habitats (Madsen 1997). Eurasian watermilfoil has been associated with declines in native plant species richness and diversity (Madsen et al. 1991a, 1991b; Madsen and Wersal 2008), reductions in habitat complexity resulting in reduced macroinvertebrate abundance (Krull 1970, Keast 1984), and reductions in fish growth (Lillie and Budd 1992). Eurasian watermilfoil poses nuisance problems to humans by impeding navigation, limiting recreation opportunities, and increasing flood frequency and intensity (Madsen et al. 1991a). It is primarily spread by fragmentation and can be easily transported between waterbodies by many vectors. Currently, Eurasian watermilfoil is becoming increasingly problem-atic in the Pacific Northwest, with significant nuisance populations of this

submersed invasive species already formed in the reservoirs of the Lower Clark Fork River (Madsen and Wersal 2008, Madsen and Cheshier 2009).

Controlling Eurasian watermilfoil in flowing systems, such as the Lower Clark Fork River, has been inconsistent and unpredictable. Therefore, there is considerable interest in developing cost-effective and efficacious operational strategies for run-of-the-river reservoirs that populate the Lower Clark Fork and similar river systems. Herbicide applications in these systems are typically subject to more extreme environmental variables than applications in lakes. Most notably, run-of-the-river reservoirs have variable water exchange patterns that will impact aqueous distribution of herbicides, resulting in reduced chemical exposure times against target plants, and unacceptabel effectiveness. Herbicide concentration exposure time (CET) relationships designed to provide excellent plant control have been developed specifically for Eurasian watermilfoil using triclopyr and endothall alone (Netherland et al. 1991, Netherland and Getsinger 1992). Small plot and whole lake studies have verified these CET relationships and documented the efficacy range for herbicide rates, as well as selectively removing Eurasian watermilfoil populations with little to no harm to native plant communities (Getsinger et al. 1997, 2000; Poovey et al. 2004; Wersal et al. 2010a).

Since Noxon Rapids Reservoir experiences routine high flow rates, as this impoundment is used for hydro-power generation, these flow rates could shorten exposure time and reduce the efficacy of triclopyr applied alone. To mitigate the short herbicide exposure times, CET relationships should be developed for combining a systemic herbicide such as triclopyr with the contact herbicide endothall, offering greater efficacy in these high-flow situations. This combination may offer the long-term systemic control of triclopyr, but reduce the contact time needed for improved control by the addition of the fast-acting endothall (Madsen et al. 2010). However, field assessment of CET relationships when these two herbicides are combined has been only limited. Furthermore, the combination would also target the invasive monocot, curlyleaf pondweed, which is not typically affected by label rates of triclopyr (Netherland et al. 2000, Poovey et al. 2002).

Objectives

The primary objective of this section of the work was to assess changes in submersed plant populations treated with the herbicides triclopyr and endothall. This assessment included determining herbicide efficacy against

the invasive plants Eurasian watermilfoil and curlyleaf pondweed, and evaluating the impact of this herbicide combination on surrounding non-target native plants. Once determined, this information can be used to develop guidance for prescriptive herbicide application techniques (dose and product delivery) to maximize the species-selective control of Eurasian watermilfoil and curlyleaf pondweed.

Materials and methods

Point intercept assessments

Pretreatment point intercept surveys were conducted from 24-25 July 2009 using a 50-m grid to assess the plant community in four plots on Noxon Rapids Reservoir prior to herbicide application. This initial assessment was identified as the 0 week after treatment (WAT) sampling interval. Similar surveys were conducted from 3-5 September 2009 (5 WAT), and 21-23 July 2010 (52 WAT) to assess both the short-term and long-term treatment efficacy on Eurasian watermilfoil and curlyleaf pondweed, and the native plant community.

The plot locations within the reservoir are depicted in Figure 30. Plots for this demonstration project were paired to assess herbicide treatments in open water (non-protected) and shoreline (more protected) areas. Pairing consisted of one treated plot and one untreated reference plot for each area (open water or shoreline). Plot 1 (8.2 ha) was treated with a combination of triclopyr and endothall, and represented an open-water treatment. Plot 2 (9.6 ha) served as the untreated reference to Plot 1. Plot 3 (7.7 ha) was also treated with a combination of triclopyr and endothall, and served as a shoreline treatment. Plot 4 (11.6 ha) served as the untreated reference to Plot 3.

Survey methods were similar to those utilized during recent projects in the Pacific Northwest (Madsen and Wersal 2008, 2009; Wersal et al. 2010a). A total of 36, 38, 32, and 30 points were surveyed in Plots 1, 2, 3, and 4, respectively. The surveys were conducted by boat using Global Positioning System (GPS) technology. A Dell Latitude E 6400 XFR (Round Rock, Texas) ruggedized computer outfitted with a Trimble AgGPS106tm (Sunnyvale, California) GPS receiver was used to navigate to each point. Survey accuracy was 3-10 ft (1-3 m) depending on satellite reception. At each survey point, a weighted thatch rake was deployed twice to determine the presence of plant species. Spatial data were recorded electronically using FarmWorks Site

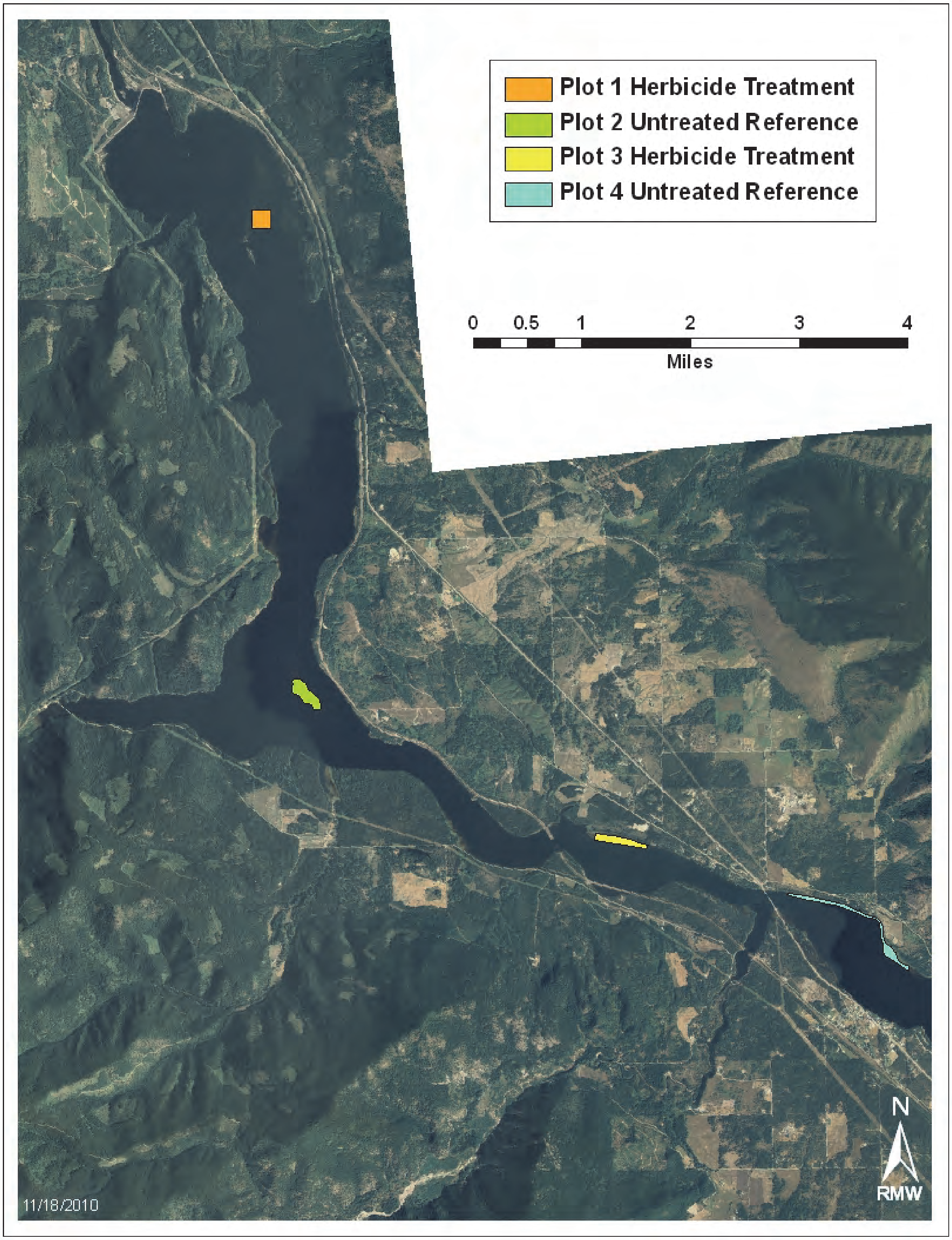

Figure 30. Herbicide-treated and untreated reference demonstration plots on Noxon Rapids Reservoir, Montana, 2009-2010.

Mate® software (Hamilton, Indiana). The software allowed for in-field geographic and attribute data collection. Data were recorded in database templates using specific pick lists constructed exclusively for this project. Site Mate® provided an environment for displaying geographic and attribute data, and enabled navigation to specific locations on the lake.

Environmental monitoring

A YSI 550A dissolved oxygen (DO) meter with a water temperature sensor (Yellow Springs, Ohio) was used to measure DO and water temperature within herbicide-treated and untreated reference plots in the reservoir. Depth profiles of DO and water temperature were created for each plot in the days prior to herbicide application, the day of herbicide application, and 5 WAT. Data were recorded in 0.5-m intervals through the water column in the center of each plot and outside of each plot. Measurements taken outside the plots were obtained in deeper water ($\geq$ 7.6 m), 5 m outside the treatment boundary, and in the absence of plants. For reporting purposes, means ($\pm$ SE) are given for each date, time, plot, and location with respect to each plot.

Statistical analysis

Plant species presence was averaged over all points sampled and multiplied by 100. Changes in the occurrence of plant species between the pre-treatment, 5-WAT, and 52-WAT surveys were determined using a Cochran-Mantel-Haenszel test, controlling for time (Stokes et al. 2000). This test assesses the differences in the correlated proportions within a given data set between variables that are not independent, in this case sampling the same points within a plot over time. Mean species richness, native species richness, and non-native species richness were calculated for each plot and subjected to a Mixed Procedures Analysis with plot as a repeated measures variable (Littell et al. 1996). The model determined differences in species richness within a given plot among sampling times. If a significant treatment effect was observed, means were separated using least squares means and grouped using the least significant difference method. All analyses were conducted using SAS® analytical software (Cary, North Carolina), at a $p < 0.05$ significance level.

Results and Discussion

Point Intercept assessments

Plot 1- Herbicide treatment, 30 July 2009

The presence of Eurasian watermilfoil in Plot 1 (open-water plot) significantly declined from 66% before herbicide treatment to 8% at 5 WAT, and to 14% at 52 WAT. This represented 88% and 80% reductions in the presence of Eurasian watermilfoil at 5 and 52 WAT, respectively (Table 10). The locations of remaining Eurasian watermilfoil after treatment were primarily along the southwestern boundary of the plot (Figures 31 through 33). Herbicide residues measured in the center of the southwest quadrant of the plot shown in Table A-1 were adequate for control, and dye dissipation patterns indicated good coverage in the bottom zone of the region, but some plants survived the treatment, or became re-established following treatment. It is likely that these areas represent the most suitable places for plant growth and would be most easily re-infested following herbicide applications. In addition, these points are on the edge of the plot and in shallower water, making them more susceptible to fragment establishment.

Despite evidence of re-colonization, an 80% reduction in the presence of Eurasian watermilfoil represents acceptable control for a run-of-the-river reservoir at 52 WAT. This level of efficacy was achieved by determining bulk water exchange patterns in the plot using RWT dye evaluations prior to herbicide applications. The water exchange information was then utilized to select dam operation schedules that would provide minimal water discharge and flow. Under the daytime discharge pattern, the calculated water exchange half-life for the plot was 2.3 hr, but was measured at 33 hr during nighttime dam operations (Table 1 above). The very short half-life (2.4 hr) would have caused a rapid herbicide exposure period, and very limited, if any, plant control. However, the extended half-life (33 hr) provided an herbicide exposure period that yielded acceptable efficacy. This unusual and successful "nighttime" application was supported by results from small-scale evaluations where Wersal et al. (2010b) reported no difference in Eurasian watermilfoil control using two contact herbicides, dependent upon light for activation, when applied at night compared to an application made during daylight hours. Neither endothall nor triclopyr are considered to be light-activated compounds, so a nighttime application should not impact plant uptake and efficacy.

Table 10. Aquatic plant occurrence in triclopyr- and endothall-treated Plot 1, Noxon Rapids Reservoir, Montana, 2009-2010. Differences between sampling events were determined at a $p < 0.05$ significance level using a Cochran Mantel Haenszel test. An asterisk indicates a significant change from the pretreatment occurrence for each species. Mean species richness (±1SE) data were separated using the LSD method; values within a row sharing the same letter are not different at $p < 0.05$ significance level.

Plant Species	Common Name	0 WAT, % Occurrence	5 WAT, % Occurrence	52 WAT, % Occurrence	Change -/+
Butomus umbellatus	Flowering rush	0	0	0	
Ceratophyllum demersum	Coontail	80	25*	33*	-
Chara sp.	Muskgrass	26	36	28	
Elodea canadensis	Elodea	69	75	94*	+
Heteranthera dubia	Water stargrass	43	33	17*	-
Myriophyllum sibiricum	Northern watermilfoil	29	19	47	
Myriophyllum spicatum	Eurasian watermilfoil	66	8*	14*	-
Potamogeton crispus	Curlyleaf pondweed	29	0*	97*	+
Potamogeton foliosus	Leafy pondweed	11	0*	0*	-
Potamogeton illinoensis	Illinois pondweed	17	3*	0*	-
Potamogeton praelongus	Whitestem pondweed	0	0	0	
Potamogeton pusillus	Narrowleaf pondweed	0	0	0	
Potamogeton richardsonii	Clasping-leaved pondweed	17	3*	3*	-
Potamogeton zosteriformis	Flat-stemmed pondweed	0	0	3	
Ranunculus aquatilis	White water-buttercup	17	17	83*	+
Stuckenia pectinata	Sago pondweed	20	3*	78*	+
Species Richness		4.2 ± 0.3a	2.2 ± 0.2b	4.9 ± 0.2c	
Native Richness		3.3 ± 0.3a	2.1 ± 0.2b	3.9 ± 0.2a	
Non-native Richness		0.9 ± 0.1a	0.1 ± 0.0b	1.1 ± 0.1a	

While Eurasian watermilfoil had greatly declined by 5 WAT, native plant populations were still abundant in the plot (Table 10). This selective removal of Eurasian watermilfoil allowed for native populations to provide fish and wildlife habitat during the year of treatment. By 52 WAT, there was an increase in the presence of native plant species in Plot 1 (most notably, elodea, white water-buttercup, and sago pondweed), indicating that native species were re-colonizing areas previously occupied by Eurasian watermilfoil (Table 10). Recovery of these species has been documented in other Pacific Northwest reservoirs following herbicide applications (Getsinger et al. 1997, Madsen and Wersal 2009, Wersal et al. 2010a).

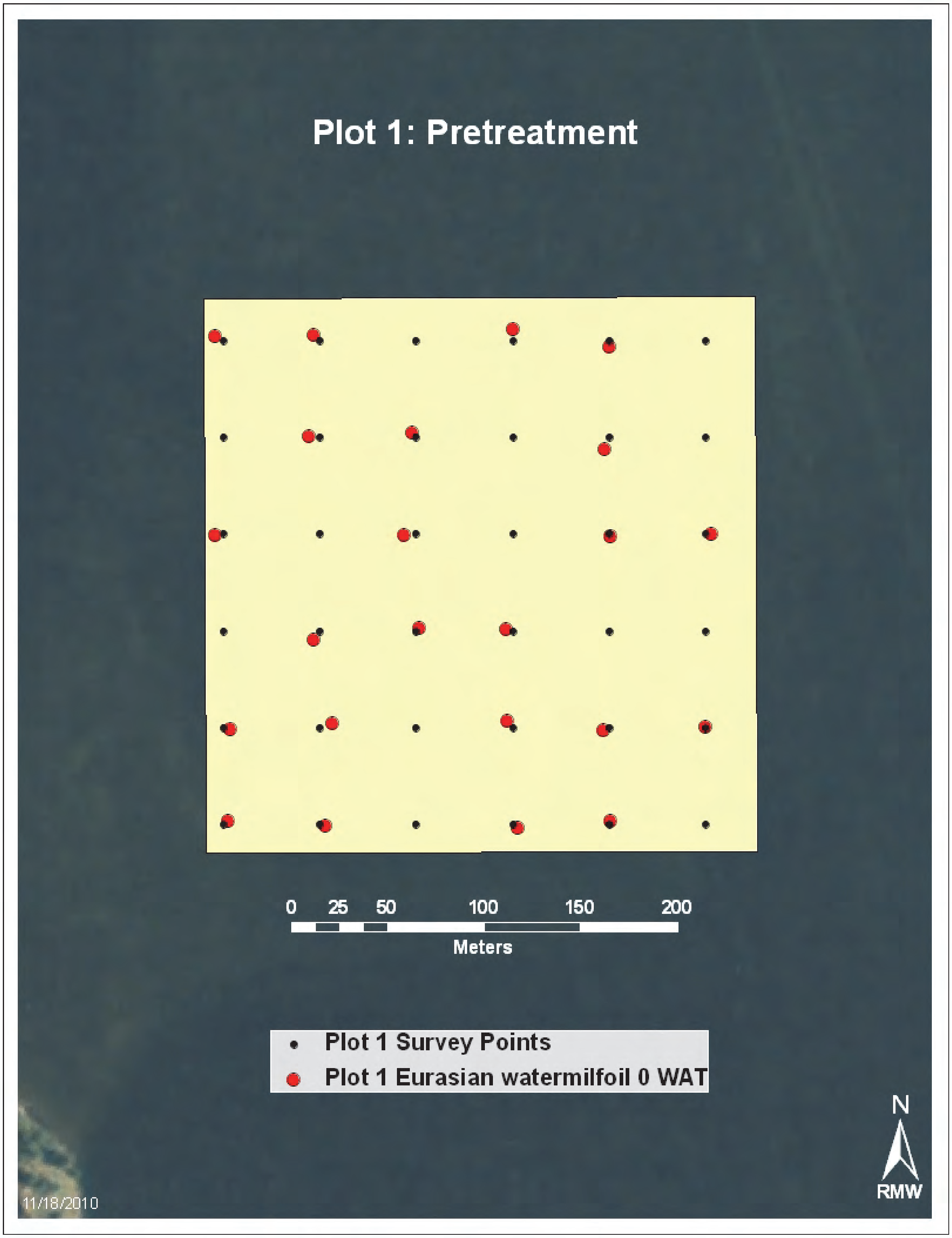

Figure 31. Locations of Eurasian watermilfoil in herbicide-treated Plot 1 during the pretreatment survey, Noxon Rapids Reservoir, Montana, July 2009.

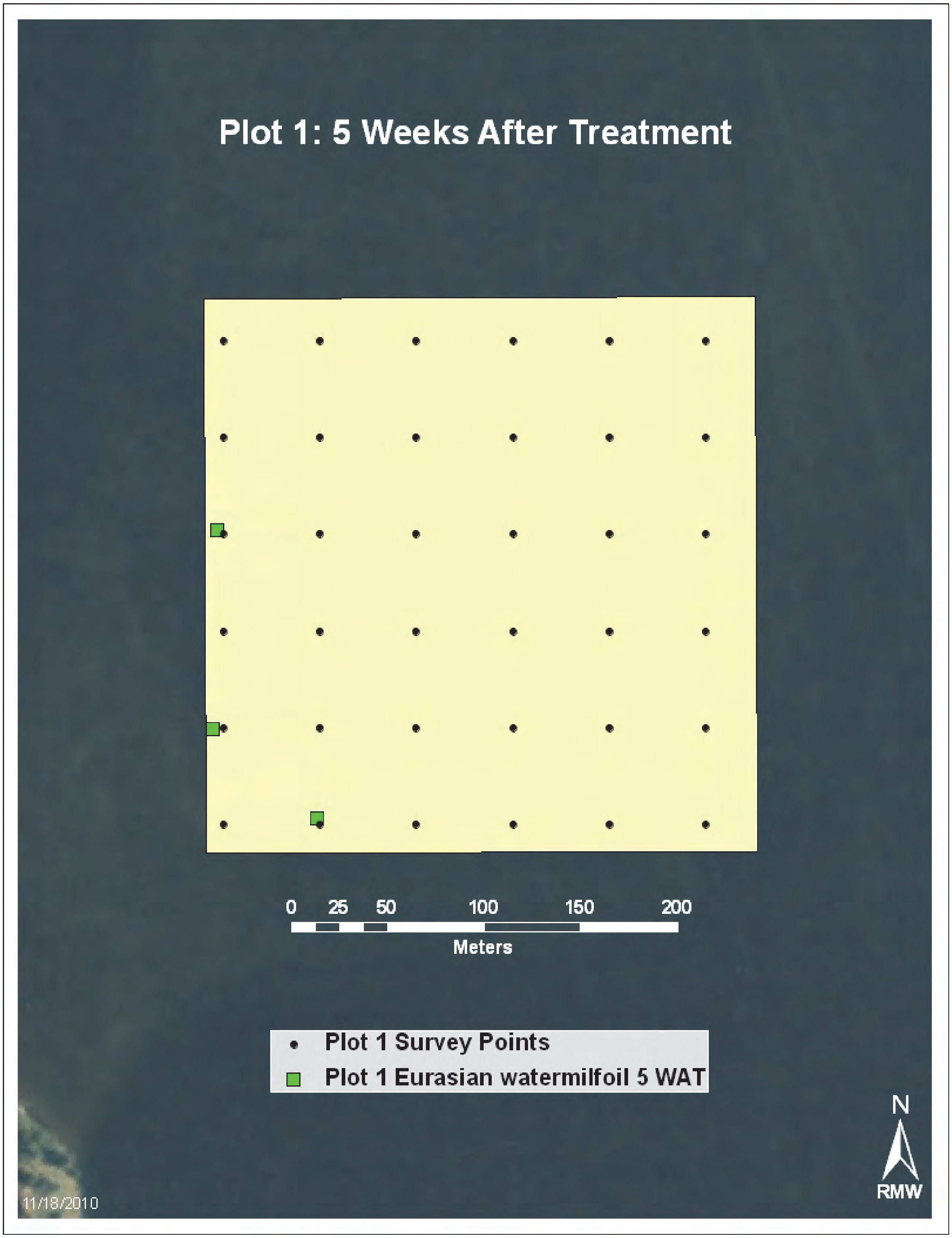

Figure 32. Locations of Eurasian watermilfoil in herbicide-treated Plot 1 at the 5 weeks after treatment survey, Noxon Rapids Reservoir, Montana, August 2009.

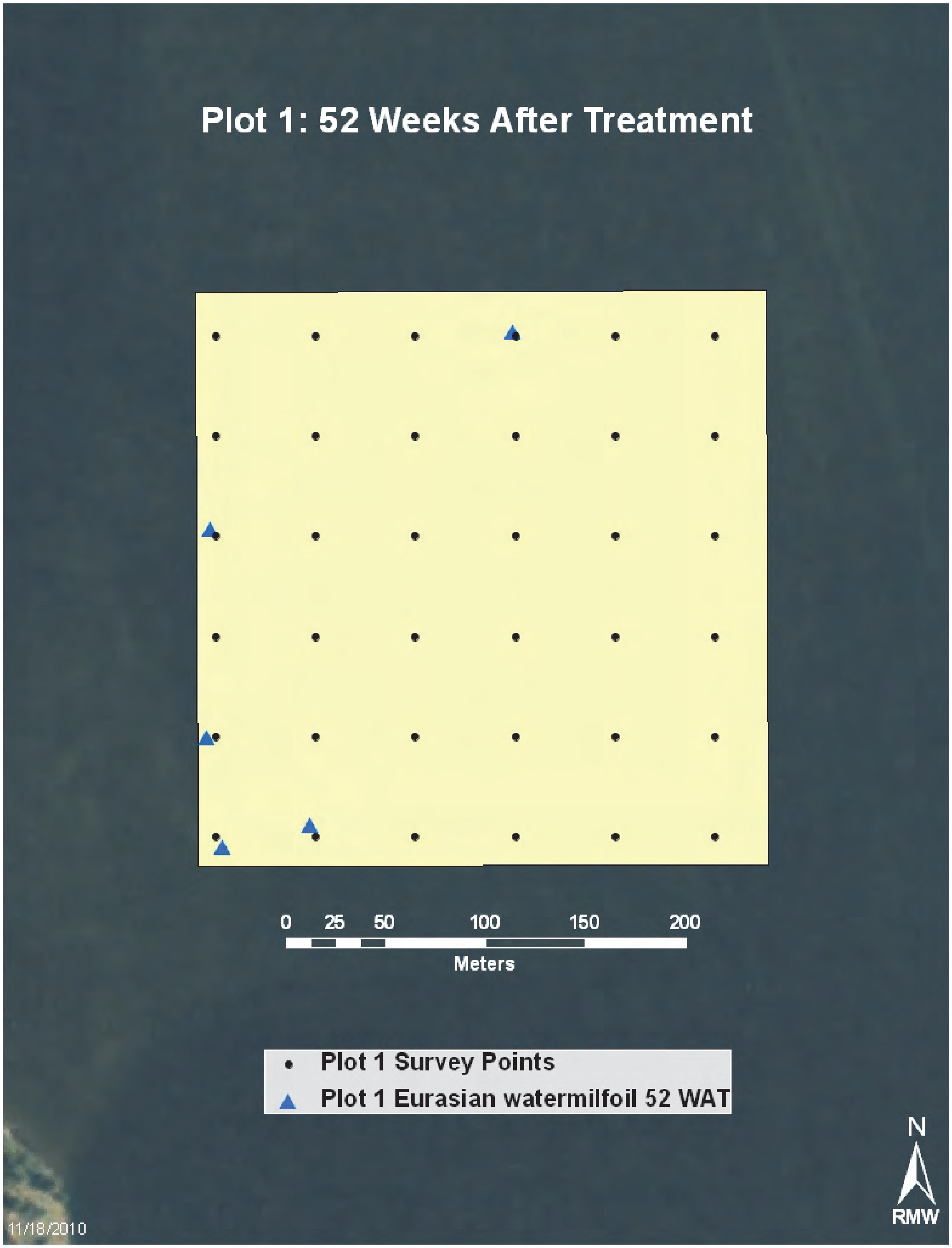

Figure 33. Locations of Eurasian watermilfoil in herbicide-treated Plot 1 at the 52 weeks after treatment survey, Noxon Rapids Reservoir, Montana, July 2010.

The presence of the native northern watermilfoil was not significantly affected by the herbicide application in this plot, indicating that it was more tolerant of the herbicide treatments than was Eurasian watermilfoil. While the presence of some native pondweeds, such as Illinois pondweed and clasping leaf pondweed, was reduced at 5 WAT, this reduction was most likely caused by endothall, which can be phytotoxic to pondweeds in certain CET scenarios.

The recovery of these species was further inhibited by the explosive growth of curlyleaf pondweed. Curlyleaf pondweed had a frequency of occurrence of 29% at 0 WAT, which was reduced to 0% at 5 WAT. However, the plant was found at 97% of sample points in Plot 1 at 52 WAT, indicating that the reduction may be attributed to the short-term efficacy of endothall, but most likely to the seasonal life history of the curlyleaf pondweed. Curlyleaf pondweed senesces in mid to late summer, over-summers as a turion on the sediment surface, and does not rely on seed production to re-colonize like Illinois pondweed and clasping leaf pondweed (Woolf and Madsen 2003).

The herbicide applications were conducted after curlyleaf pondweed had initiated turion production; therefore, even if the plants were ultimately killed by the endothall, viable turions had already been produced and deposited on the sediment awaiting fall sprouting conditions. In order to significantly reduce curlyleaf pondweed levels, and eliminate turion production, innovative strategies must be evaluated for applications earlier in the growing season, or in late fall when turions begin to sprout. However, several problems must be overcome: a) water flows are high during spring months, greatly reducing herbicide exposure times, which may result in little or no control; and b) the seasonal phenology of curlyleaf pondweed may be delayed depending upon water temperatures, which will ultimately limit the applicability of some methods and herbicides. Therefore, late fall may be the most opportune time to evaluate the success of herbicides in controlling curlyleaf pondweed in the Lower Clark Fork River system.

Total species richness in Plot 1 increased from 4.2 species per point during pre-treatment surveys to 4.9 species per point by 52 WAT. Some impacts were detected on the non-target plant populations at 5 WAT; however, the plant community recovered by 52 WAT. The increase in total species richness was due in large part to a significant increase in native species richness at 52 WAT, when compared to the pre-treatment survey. There was a decrease in non-native species richness at 5 WAT largely due to reductions

in Eurasian watermilfoil. However, there was no difference in non-native species richness at 52 WAT when compared to the pre-treatment survey; a result driven by the widespread occurrence of curlyleaf pondweed in 2010.

Plot 2-Untreated reference

The presence of plants in the untreated reference (Plot 2) changed little from the initial survey to the 52-week survey (Table 11). The lack of change in the presence of Eurasian watermilfoil in Plot 2 indicates that reductions in Plot 1 were due to the herbicide application and not natural senescence. Eurasian watermilfoil was found during the 5- and 52-week surveys at points where it was absent during the pretreatment survey (Figures 34 through 36), but this was not a major expansion. While the presence of elodea, white water-buttercup, and sago pondweed did not change in this untreated plot, these plants did not undergo a rapid colonization of the plot, as occurred in Plot 1 when Eurasian watermilfoil was selectively removed by the herbicide treatment.

Curlyleaf pondweed occurrence in Plot 2 remained fairly constant from the initial survey (24%) to the 5-week survey (21%). This situation suggests that endothall had some effect on curlyleaf pondweed reduction in Plot 1 over the same time period. However, by the 52-week survey, the presence of curlyleaf pondweed had increased to 83% in Plot 2. These results confirm the need of a thorough understanding of the life history of this species for the Pacific Northwest reservoirs if management strategies are to be effective.

Total species richness in Plot 2 also increased from the initial survey to the 52-week survey. The condition was most likely due to the increased presence of non-native species - influenced in large part by curlyleaf pondweed, which was found at 24% of the points during the initial survey and at 83% of the points during the 52-week survey. Native species richness did not change in Plot 2 over the course of the study, suggesting that by not managing Eurasian watermilfoil, long-term negative impacts to the native plant community might occur. Total species richness in nearby Lake Pend Oreille, Idaho, was significantly less in untreated areas than in areas that had received herbicide applications the previous year (Madsen and Wersal 2009).

Table 11. Aquatic plant occurrence in untreated reference Plot 2, Noxon Rapids Reservoir, Montana, 2009-2010. Differences between sampling events were determined at a $p < 0.05$ significance level using a Cochran Mantel Haenszel test. An asterisk indicates a significant change from the pretreatment occurrence for each species. Mean species richness (±1SE) data were separated using the LSD method; values within a row sharing the same letter are not different at $p < 0.05$ significance level.

Plant Species	Common Name	0 WAT, % Occurrence	5 WAT, % Occurrence	52 WAT, % Occurrence	Change -/+
Butomus umbellatus	Flowering rush	8	0	0	
Ceratophyllum demersum	Coontail	63	63	62	
Chara sp.	Muskgrass	3	3	7	
Elodea canadensis	Elodea	53	74	48	
Heteranthera dubia	Water stargrass	0	13*	10*	+
Myriophyllum sibiricum	Northern watermilfoil	3	3	17*	+
Myriophyllum spicatum	Eurasian watermilfoil	68	71	83	
Potamogeton crispus	Curlyleaf pondweed	24	21	83*	+
Potamogeton foliosus	Leafy pondweed	8	58*	31*	+
Potamogeton illinoensis	Illinois pondweed	16	8	14	
Potamogeton praelongus	Whitestem pondweed	5	5	0	
Potamogeton pusillus	Narrowleaf pondweed	0	0	0	
Potamogeton richardsonii	Clasping-leaved pondweed	24	24	31	
Potamogeton zosteriformis	Flat-stemmed pondweed	0	0	3	
Ranunculus aquatilis	White water-buttercup	5	0	10	
Stuckenia pectinata	Sago pondweed	42	24	38	
Species Richness		3.2 ± 0.2a	3.6 ± 0.2a	4.3 ± 0.3b	
Native Richness		2.2 ± 0.2a	2.7 ± 0.2a	2.6 ± 0.3a	
Non-native Richness		1.0 ± 0.1a	0.9 ± 0.1a	1.6 ± 0.1b	

Plot 3 – Herbicide treatment, 28 July 2009

Similar to Plot 1, Eurasian watermilfoil presence in Plot 3 (shoreline plot) was significantly reduced from 50% during the pre-treatment survey to 10% at 5 WAT and 3% at 52 WAT. This represents an 80% reduction at 5 WAT, and a 94% reduction at 52 WAT in the presence of Eurasian watermilfoil (Table 12). At 5 and 52 WAT, remaining Eurasian watermilfoil was observed along the upstream shoreline (Figures 37 through 39). Several factors may have contributed to these plants surviving the treatment. At the time of

Figure 34. Locations of Eurasian watermilfoil in untreated reference Plot 2 at the initial survey, Noxon Rapids Reservoir, Montana, July 2009.

Figure 35. Locations of Eurasian watermilfoil in untreated reference Plot 2 at the 5-week survey, Noxon Rapids reservoir, Montana, August 2009.

Figure 36. Locations of Eurasian watermilfoil in untreated reference Plot 2 at the 52-week survey, Noxon Rapids Reservoir, Montana, August 2010.

Table 12. Aquatic plant occurrence in triclopyr + endothall treated Plot 3, Noxon Rapids Reservoir, MT, 2009-2010. Differences between sampling events were determined at a $p < 0.05$ significance level using a Cochran Mantel Haenszel test. An asterisk indicates a significant change from the pretreatment occurrence for each species. Mean species richness (±1SE) data were separated using the LSD method; values within a row sharing the same letter are not different at $p < 0.05$ significance level.

Plant Species	Common Name	0 WAT, % Occurrence	5 WAT, % Occurrence	52 WAT, % Occurrence	Change -/+
Butomus umbellatus	Flowering rush	0	0	3	
Ceratophyllum demersum	Coontail	38	16	23	
Chara sp.	Muskgrass	16	19	11	
Elodea canadensis	Elodea	59	58	58	
Heteranthera dubia	Water stargrass	6	6	3	
Myriophyllum sibiricum	Northern watermilfoil	34	10*	45*	+
Myriophyllum spicatum	Eurasian watermilfoil	50	10*	3*	-
Potamogeton crispus	Curlyleaf pondweed	3	0	55*	+
Potamogeton foliosus	Leafy pondweed	25	6*	26	
Potamogeton illinoensis	Illinois pondweed	0	0	0	
Potamogeton praelongus	Whitestem pondweed	0	0	0	
Potamogeton pusillus	Narrowleaf pondweed	0	0	0	
Potamogeton richardsonii	Clasping-leaved pondweed	18	0*	3	-
Potamogeton zosteriformis	Flat-stemmed pondweed	0	0	3	
Ranunculus aquatilis	White water-buttercup	0	10	55*	+
Stuckenia pectinata	Sago pondweed	13	3	52*	+
Species Richness		2.7 ± 0.3a	1.3 ± 0.2b	3.5 ± 0.5a	
Native Richness		2.2 ± 0.2a	1.2 ± 0.2b	2.9 ± 0.4a	
Non-native Richness		0.5 ± 0.1a	0.1 ± 0.0b	0.6 ± 0.1a	

application, water depth was too shallow to place herbicide directly around these plants, and water movement may have carried the herbicide down-stream too rapidly to maintain a lethal dose in that portion of the plot (Figure 2 above). In fact, dye and herbicide residues within the plot were lowest in the upstream areas where the remaining Eurasian watermilfoil was observed (Table A2). Greater control was achieved in the middle and down-stream portions of the plot where herbicide concentrations were higher.

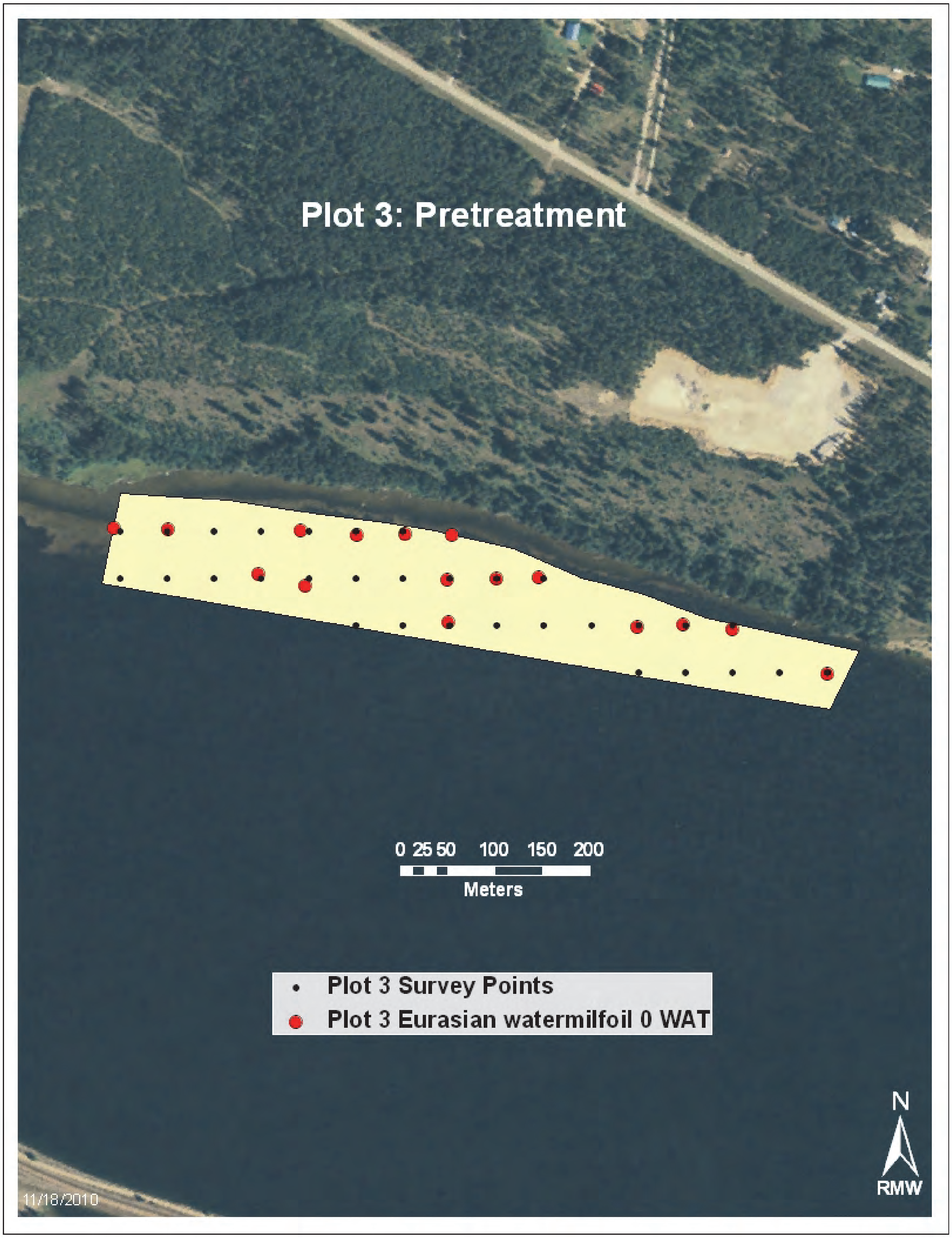

Figure 37. Locations of Eurasian watermilfoil in herbicide-treated Plot 3 during the pretreatment survey, Noxon Rapids Reservoir, Montana, July 2009.

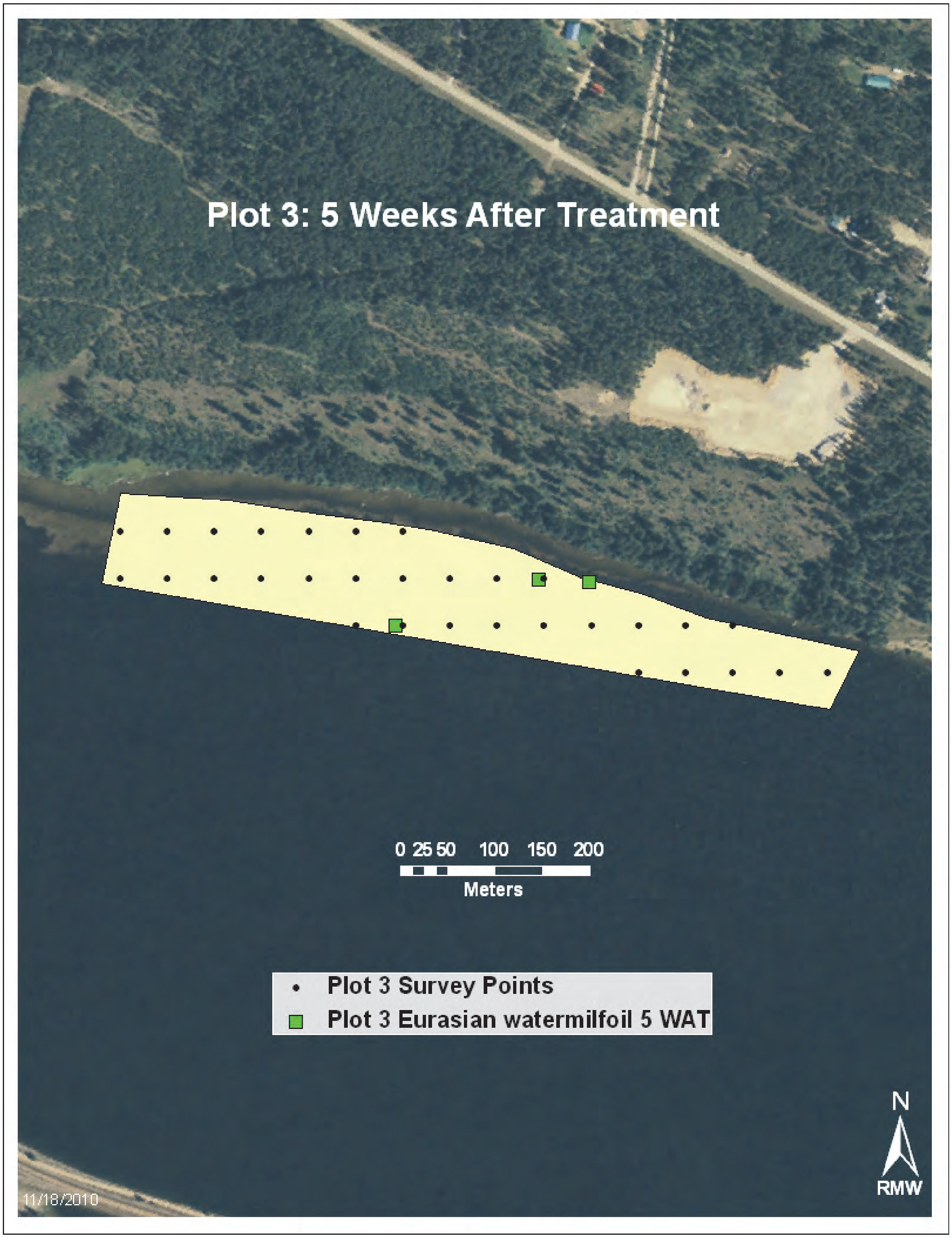

Figure 38. Locations of Eurasian watermilfoil in herbicide-treated Plot 3 at the 5-WAT survey, Noxon Rapids Reservoir, Montana, August 2009.

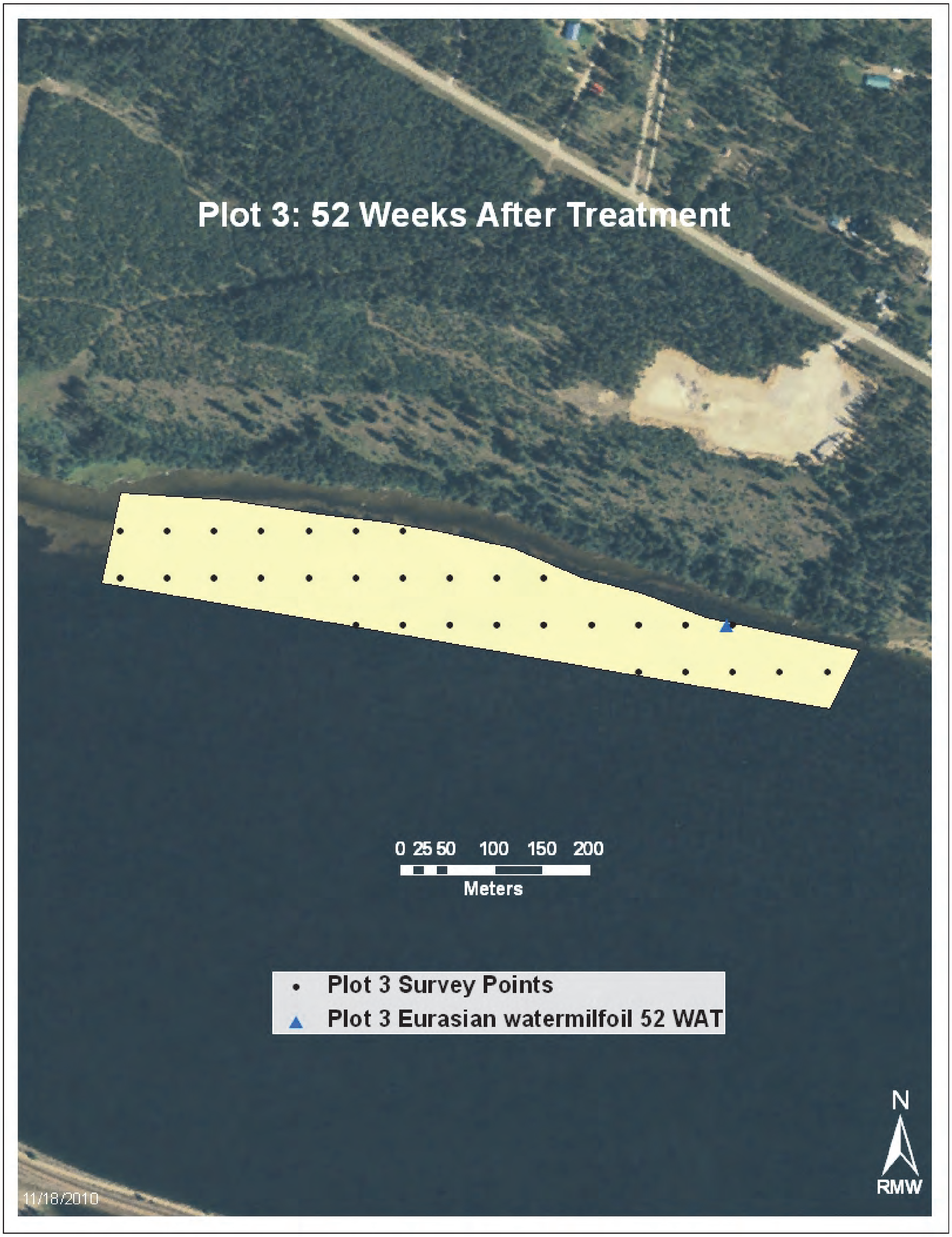

Figure 39. Locations of Eurasian watermilfoil in herbicide-treated Plot 3 at the 52-WAT survey, Noxon Rapids Reservoir, Montana, July 2010.

Native species were much less affected in Plot 3 than in Plot 1, which may be due to the increased endothall exposure time attained in Plot 1. Similar results were reported in Hayden Lake, Idaho, where impacts to the native submersed plant community by herbicide applications were minimal, with some species increasing in occurrence (Wersal et al. 2010a). The whole plot water exchange half-life in Plot 3 was 16 hr as compared to 33 hr in Plot 1 (Table 1). Coontail, elodea, water stargrass, and leafy pondweed were not greatly impacted by the herbicide treatment at 5 or 52 WAT. The presence of northern watermilfoil, white water-buttercup, and sago pondweed increased at 52 WAT, following the removal of Eurasian watermilfoil. Data from Plots 1 and 3 suggest that there may be a CET threshold for this combination treatment (triclopyr+endothall) that lies somewhere between 15 and 30 hr. Once exceeded, this threshold will result in some injury to the native plant community, though additional studies will be required to confirm such a threshold. However, there will also be a trade-off with CET relationships and Eurasian watermilfoil control. Most notably, if herbicide exposure times are reduced to minimize non-target plant injury, there is potential to minimize Eurasian watermilfoil control. More information on herbicide CET relationships for local native plant species will help to refine species selective treatment strategies on the reservoir.

The native plant flat-stemmed pondweed was observed for the first time in Plot 3 at 52 WAT, as well as the invasive flowering rush. Curlyleaf pondweed was observed at 3% of the sample points at 0 WAT, but declined by 5 WAT, probably due to the effects of endothall in the combination treatment. Similar to Plots 1 and 2, presence of curlyleaf pondweed increased to 55% at the 52-week sampling event. An increase in curlyleaf pondweed in both treated plots suggests that applying herbicides after turion formation (July and August) will not provide long-term control of this species.

Species richness (total, native, and non-native) declined from the 0- to 5-WAT survey, indicating some impacts to the plant community. However, by 52 WAT there was no difference in any of the richness measurements, which was due to the recovery of some native species following the herbicide application, the appearance of new native and non-native species, and the increase in curlyleaf pondweed that influenced non-native species richness. In Lake Pend Oreille, Idaho, there was also no significant impact to native species richness one year after treatment with most treatment methods (Madsen and Wersal 2009).

Plot 4 – Untreated reference

The plant community in the untreated reference Plot 4 did not change with the exception of elodea, curlyleaf pondweed, and clasping-leaf pondweed (Table 13). Similar to the other plots, the presence of curlyleaf pondweed increased from the initial survey to the 52-week survey. However, the presence of elodea declined by 52 weeks, likely a response to increasing non-native species such as curlyleaf pondweed and flowering rush. Native submersed aquatic plants can be negatively impacted by the invasion and expansion of non-native species (Madsen et al. 1991b; Madsen and Wersal 2008; Madsen 1994). Eurasian watermilfoil was observed at 47, 57, and 31% of all sample points during the initial, 5-, and 52-week surveys, respectively (Table 13, Figures 40 through 42). The lack of change in the presence of Eurasian watermilfoil in Plot 4 indicates that reductions in Plot 3 were due to the herbicide application and not natural senescence. Similar to other plots, curlyleaf pondweed increased in occurrence from 7% at the initial survey to 47% at 52 weeks.

Environmental monitoring

The DO and water temperature values within, and outside of, herbicide treated and untreated reference plots are summarized in Tables 14 through 17. These measurements showed little difference among sampling locations over time. In herbicide-treated plots (1 and 3), water temperature ranged from 21.1 to 24.4 °C, and DO ranged from 8.1 to 13.3 mg/L during the sampling period. In untreated reference plots (2 and 4), water temperature ranged from 20.6 to 24.5 °C, and DO ranged from 8.1 to 11.8 mg/L during the sampling period.

In most cases, DO levels were slightly higher at stations within the plots than outside the plots. This was likely due to actively growing stands of submersed plants within the plots, versus an absence of plants in the deeper waters outside the plots. During pretreatment sampling, vegetation in the herbicide-treated plots was dominated by a community of invasive plants, primarily Eurasian watermilfoil, and a variety of native plants. However, at post-treatment, the community was primarily composed of native plants, since most of the Eurasian watermilfoil had been selectively removed by the herbicides. In all cases, the DO concentrations measured in and around all plots were 160-265 % above optimal levels ($\geq$ 5 mg/L) required to support healthy fish populations. Reports identified that most warm-water fish generally die when exposed to DO concentrations lower than about

Table 13. Aquatic plant occurrence in untreated reference Plot 4, Noxon Rapids Reservoir, Montana, 2009-2010. Differences between sampling events were determined at a $p < 0.05$ significance level using a Cochran Mantel Haenszel test. An asterisk indicates a significant change from the pretreatment occurrence for each species. Mean species richness (±1SE) data were separated using the LSD method, values within a row sharing the same letter are not different at $p < 0.05$ significance level.

Plant Species	Common Name	0 WAT, % Occurrence	5 WAT, % Occurrence	52 WAT, % Occurrence	Change -/+
Butomus umbellatus	Flowering rush	0	0	3	
Ceratophyllum demersum	Coontail	37	57	53	
Chara sp.	Muskgrass	7	7	6	
Elodea canadensis	Elodea	10	47	28*	-
Heteranthera dubia	Water stargrass	10	0	3	
Myriophyllum sibiricum	Northern watermilfoil	20	20	31	
Myriophyllum spicatum	Eurasian watermilfoil	47	57	31	
Potamogeton crispus	Curlyleaf pondweed	7	0	47*	+
Potamogeton foliosus	Leafy pondweed	27	33	13	
Potamogeton illinoensis	Illinois pondweed	0	0	3	
Potamogeton praelongus	Whitestem pondweed	0	0	0	
Potamogeton pusillus	Narrowleaf pondweed	0	0	0	
Potamogeton richardsonii	Clasping-leaved pondweed	0	7	19*	+
Potamogeton zosteriformis	Flat-stemmed pondweed	0	0	3	
Ranunculus aquatilis	White water-buttercup	27	0*	19	
Stuckenia pectinata	Sago pondweed	23	20	22	
Species Richness		2.6 ± 0.3a	2.5 ± 0.2a	2.8 ± 0.4a	
Native Richness		2.1 ± 0.2a	1.9 ± 0.2a	1.9 ± 0.3a	
Non-native Richness		0.5 ± 0.1a	0.6 ± 0.1a	0.8 ± 0.1a	

1.5 mg/L for extended periods, although species-specific values may be slightly different (Moss and Scott 1961, Smale and Rabeni 1995). The DO levels measured during this study rarely dropped below 8 mg/L and never below 7.5 mg/L. Moreover, water in contact with the atmosphere generally reaches a saturation point at a concentration of approximately 10 mg/L at 15 °C (Kramer 1987).

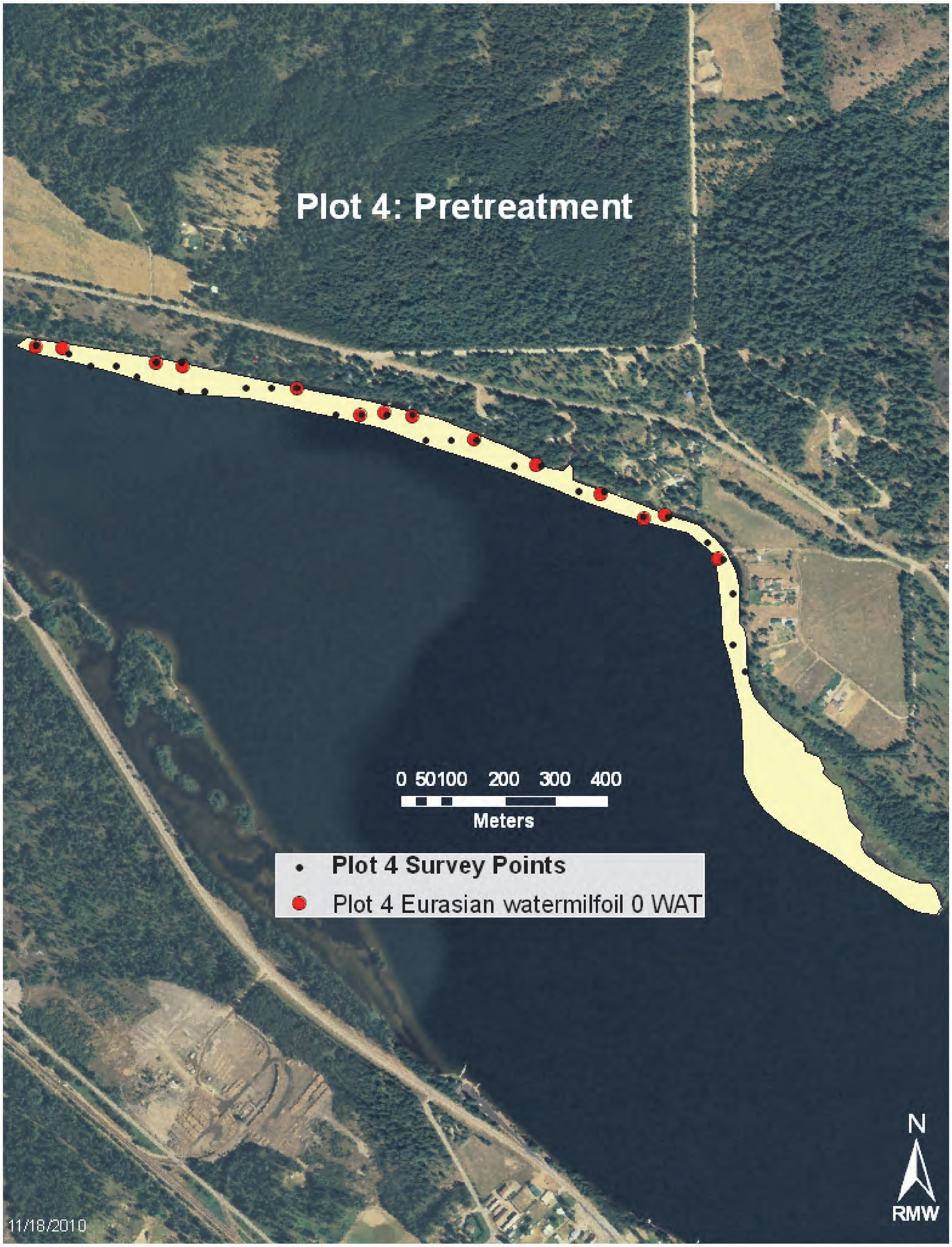

Figure 40. Locations of Eurasian watermilfoil in untreated reference Plot 4 at the initial survey, Noxon Rapids Reservoir, Montana, July 2009.

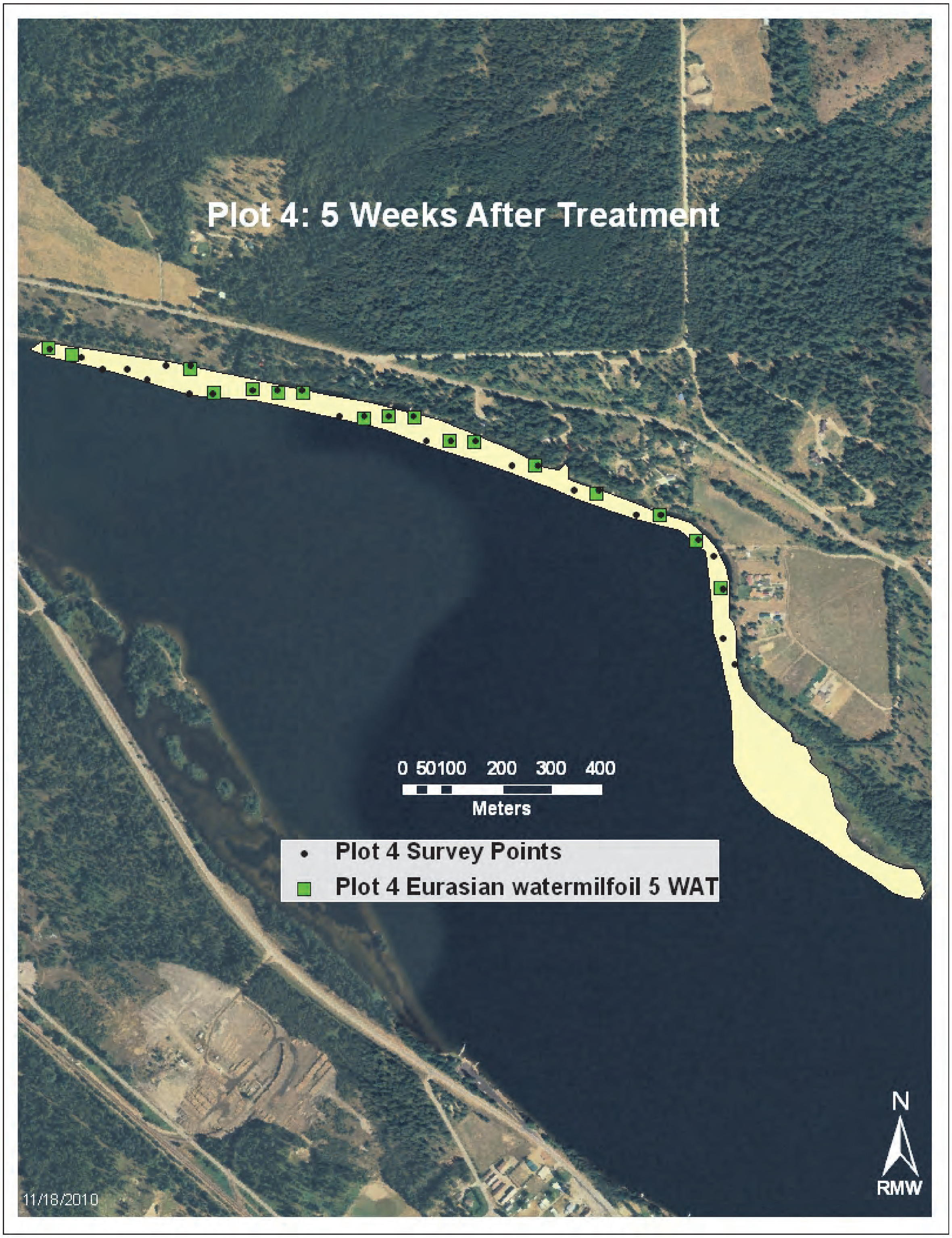

Figure 41. Locations of Eurasian watermilfoil in untreated reference Plot 4 at the 5-week survey, Noxon Rapids Reservoir, Montana, August 2009.

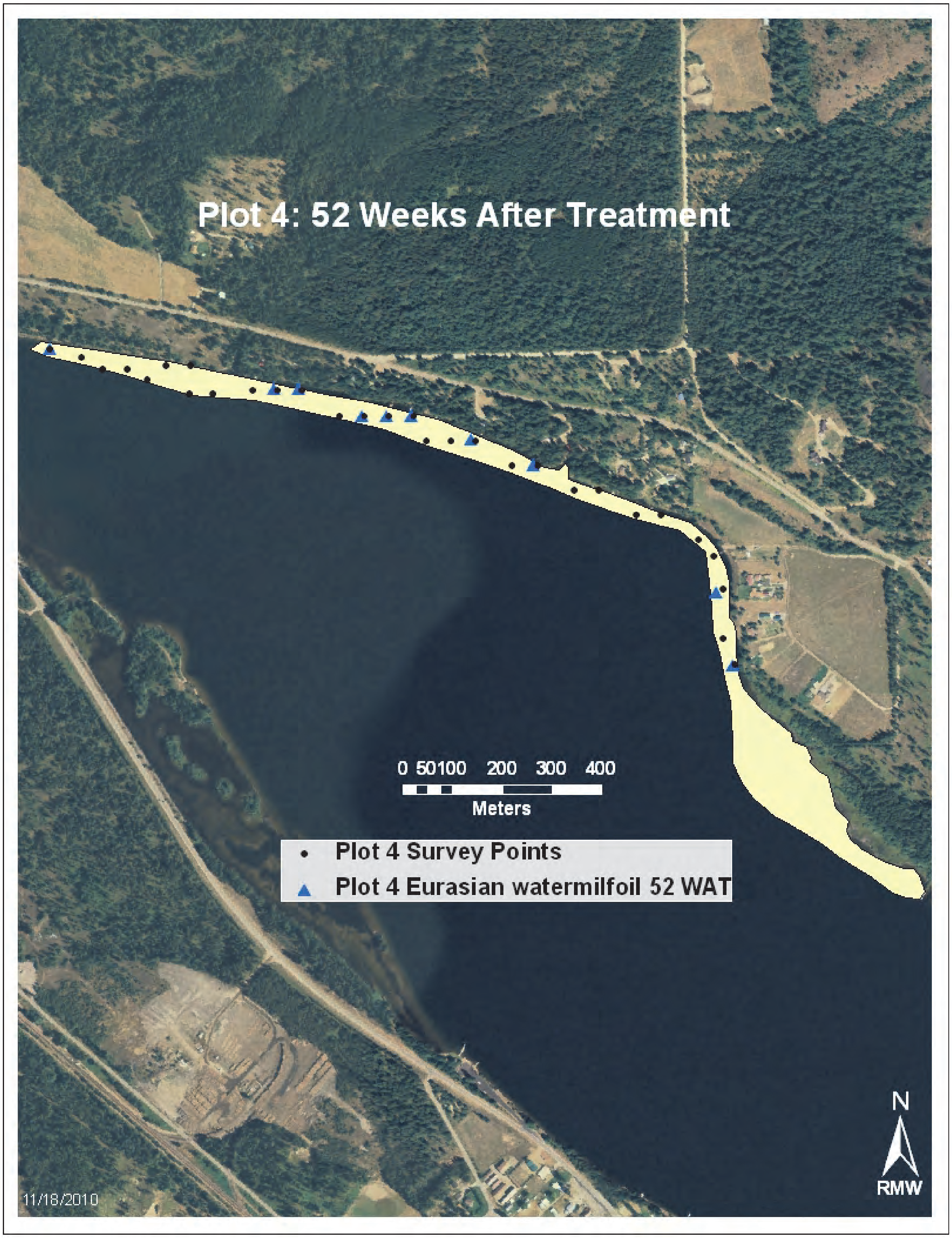

Figure 42. Locations of Eurasian watermilfoil in untreated reference Plot 4 at the 52-week survey, Noxon Rapids Reservoir, Montana, July 2010.

Table 14. Mean (±1SE) water quality measurements for herbicide-treated Plot 1 in Noxon Rapids Reservoir, Montana, from July to September 2009. Herbicide application occurred 30 July 2009.

Date	Time (h)	Location I=Inside Plot O=Outside Plot	DO (mg L^{-1})	Water Temperature (°C)
7/24/2009	0748	O	8.09 ± 0.03	21.5 ± 0.05
	0800	I	8.97 ± 0.16	22.0 ± 0.00
7/30/2009	0630	I	8.64 ± 0.09	22.9 ± 0.02
	0643	O	8.11 ± 0.07	22.8 ± 0.10
	0930	O	8.16 ± 0.08	22.8 ± 0.08
	0941	I	8.18 ± 0.02	22.8 ± 0.02
	1204	O	8.23 ± 0.08	22.9 ± 0.10
	1215	I	8.92 ± 0.07	23.1 ± 0.07
	1535	O	8.56 ± 0.10	23.6 ± 0.17
	1543	I	9.26 ± 0.23	24.0 ± 0.05
9/4/2009	1006	I	8.72 ± 0.02	21.1 ± 0.00
	1015	O	8.66 ± 0.07	21.4 ± 0.03

Table 15. Mean (±1SE) water quality measurements for untreated reference Plot 2, Noxon Rapids Reservoir, Montana, from July to September 2009.

Date	Time (h)	Location I=Inside Plot O=Outside Plot	DO (mg L^{-1})	Water Temperature (°C)
7/23/2009	1114	I	8.95 ± 0.24	22.3 ± 0.06
	1123	O	8.73 ± 0.02	22.0 ± 0.11
7/30/2009	1228	O	8.10 ± 0.06	23.1 ± 0.07
	1237	I	8.94 ± 0.11	23.4 ± 0.10
9/4/2009	1400	O	8.54 ± 0.11	21.0 ± 0.07
	1407	I	11.79 ± 0.25	21.7 ± 0.10

Table 16. Mean (±1SE) water quality measurements for herbicide-treated Plot 3, Noxon Rapids Reservoir, Montana, from July to September 2009. Herbicide application occurred on 28 July 2009.

Date	Time (h)	Location I=Inside Plot O=Outside Plot	DO (mg L^{-1})	Water Temperature (°C)
7/23/2009	0907	I	9.49 ± 0.05	21.2 ± 0.10
	0915	O	8.84 ± 0.07	21.5 ± 0.05
7/28/2009	0750	O	8.42 ± 0.08	22.1 ± 0.04
	0802	I	8.24 ± 0.18	22.5 ± 0.00
	1350	O	8.08 ± 0.08	22.5 ± 0.12
	1401	I	11.85 ± 0.42	24.4 ± 0.75
7/30/2009	1251	O	7.87 ± 0.10	22.7 ± 0.07
	1300	I	10.43 ± 1.28	23.4 ± 0.57
9/4/2009	1630	O	8.68 ± 0.10	21.2 ± 0.11
	1640	I	13.30 ± 0.83	22.5 ± 0.88

Table 17. Mean (±1SE) water quality measurements for untreated reference Plot 4, Noxon Rapids Reservoir, Montana, from July to September 2009.

Date	Time (h)	Location I=Inside Plot O=Outside Plot	DO (mg L^{-1})	Water Temperature (°C)
7/22/2009	1352	O	8.91 ± 0.04	21.7 ± 0.23
	1400	I	10.84 ± 0.33	22.6 ± 0.33
7/28/2009	0824	O	8.10 ± 0.06	22.3 ± 0.02
	0830	I	8.94 ± 0.11	22.4 ± 0.06
	1409	O	8.29 ± 0.02	23.1 ± 0.17
	1420	I	9.40 ± 0.48	24.5 ± 0.31
7/30/2009	1316	O	7.83 ± 0.09	22.7 ± 0.08
	1325	I	9.49 ± 0.14	23.3 ± 0.08
9/5/2009	0855	O	8.68 ± 0.07	20.7 ± 0.01
	0906	I	8.78 ± 0.10	20.6 ± 0.00

In rare cases, some ambient conditions in water bodies, in conjunction with an herbicide treatment, might trigger low DO levels and associated problems with fish. These conditions could include rapid plant death combined with warm water temperatures, limited water circulation, no inflow of oxygenated water, broad spectrum control of all plants, and

treatment of an entire water body containing stands of dense vegetation. These conditions will likely not be present in the plant stands in Noxon Rapids Reservoir as it is a cold-water, run-of-the-river reservoir, meaning there is continuous movement of cool, near-saturated, oxygenated water through plant stands. Moreover, reduced DO conditions did not occur in the treatments of 2009; and there were no observations of any stress, injury, or fish mortality in or around the herbicide-treated plots during the post-treatment periods in 2009 or 2010.

Selective control of target plants using triclopyr combined with endothall did not negatively impact DO levels in treated plots. This was not unexpected, because an extremely small percentage of the reservoir was treated (< 15 ha = < 0.5%), invasive plants were controlled in a selective manner, and active water-exchange processes occurred in the treated areas, thereby maintaining healthy DO levels. And, the DO results from the 2009 treatments are similar to what would be expected with herbicide treatments of ≥ 80 ha per year (~ 2.5% of the reservoir).

Conclusions and recommendations

Conclusions

The following conclusions can be reached based upon the research documented in this study:

- Combinations of triclopyr and endothall can effectively and selectively control Eurasian watermilfoil in 6- to 8-ha plots in Noxon Rapids Reservoir for up to 2 years (year of treatment and 1 year post treatment).
- While curlyleaf pondweed populations were controlled in the year of treatment, they were not controlled at 1 year post treatment. Long-term management of curlyleaf pondweed depends upon controlling production and sprouting of turions (not just standing biomass), and herbicide application timing will be critical.
- Abundant fish and wildlife habitat was maintained in herbicide-treated plots, as minimal impacts occurred to native plant populations, and there were no impacts on dissolved oxygen levels.
- In untreated plots, native plant populations remained suppressed and vegetation continued to be dominated by Eurasian watermilfoil.

- Understanding bulk water exchange processes in proposed treatment areas can provide guidance for prescriptive management strategies and improved invasive plant control using herbicides.
- Variable-depth application techniques can deliver a greater proportion of herbicides to the deeper zones of the water column. This delivery method should improve efficacy and reduce the amount of herbicide required to achieve plant control.

Recommendations

- Herbicide efficacy should be assessed at 2 years post treatment. This evaluation will yield important information for development of long-term management strategies and prioritization of future treatment sites.
- Chemical applications should coincide with minimal reservoir discharge events to extend aqueous herbicide exposure periods and improve efficacy against target plants.
- Herbicide evaluations should be used to develop strategies for controlling Eurasian watermiloil and curlyleaf pondweed in narrow shoreline areas to complement management activities on larger plant stands. If not managed, these smaller areas will provide sites for re-establishment of invasive plants into areas previously controlled.
- More information on herbicide concentration and exposure time relationships for local native plant species should be developed to refine species-selective management strategies against invasive plant populations on the reservoir.
- Improved and long-term control strategies for curlyleaf pondweed, based on the life cycle of the plant in the Lower Clark Fork river system, should be developed and evaluated.
- Variable-depth application techniques should be further evaluated to refine depth zone placement of products for minimal and more cost-effective use of herbicides for controlling submersed invasive plants.
- Chemical strategies for selective control of the newly invading flowering rush should be evaluated.
- Annual monitoring of plant populations and assessment of all management techniques by experienced and independent parties should be continued. Consistent evaluations, properly interpreted, will provide clear guidance for planning and successfully executing environmentally compatible and species-selective management approaches.

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Appendix A: Triclopyr and Endothall Concentration Data

Table A1. Triclopyr and endothall (μg/L) concentrations for all internal stations within Plot 1. Results are further divided by water column. Blank cells denote missing samples or those that were never taken.

Station 20	0 HAT	1 HAT	3 HAT	6 HAT	8 HAT	10 HAT	12 HAT	24 HAT	33 HAT	48 HAT
Bottom Triclopyr Concentration (ppb)	349	1315	1640	2060	610	1615	2352	2610	635	
Middle Triclopyr Concentration (ppb)	821	300	475	683	140	1010	1511	525	220	
Surface Triclopyr Concentration (ppb)	807	160	575	672	35	435	1243	425		
Bottom Endothall Concentration (ppb)	1205	755	1460	8373	252	1544	5348	6907	79	
Middle Endothall Concentration (ppb)	1510	2111	392	91	80	1101	752	30	54	
Surface Endothall Concentration (ppb)	366	9213	357	172	24	294	610	87		

Station 21	0 HAT	1 HAT	3 HAT	6 HAT	8 HAT	10 HAT	12 HAT	24 HAT	33 HAT	48 HAT
Bottom Triclopyr Concentration (ppb)	569	1915	615	780	10	135	1054	400	310	
Middle Triclopyr Concentration (ppb)	958	590	590	908	95	70	859	520	235	
Surface Triclopyr Concentration (ppb)	779	390	665	852	85	75		380	150	
Bottom Endothall Concentration (ppb)	1597	15398	319	77	12	107	133	146	58	
Middle Endothall Concentration (ppb)	1046	3796	221	113	157	4	44	82	53	
Surface Endothall Concentration (ppb)	1381	81	455	69	186	4		83	54	

Station 22	0 HAT	1 HAT	3 HAT	6 HAT	8 HAT	10 HAT	12 HAT	24 HAT	33 HAT	48 HAT
Bottom Triclopyr Concentration (ppb)	398	3140	380	905	1155	1350	935	1525	0	380
Middle Triclopyr Concentration (ppb)	402	105	270	634	20	115	1056	735	570	440
Surface Triclopyr Concentration (ppb)	726	65	255	771	245	335	1075	565	560	0
Bottom Endothall Concentration (ppb)	1326	204	111	205	1349	182	205	1623	78	189
Middle Endothall Concentration (ppb)	1634	42	71	0	0	40	19	57	72	363
Surface Endothall Concentration (ppb)	1410	419	55	54	273	63	64	96	74	59

Station 23	0 HAT	1 HAT	3 HAT	6 HAT	8 HAT	10 HAT	12 HAT	24 HAT	33 HAT	48 HAT
Bottom Triclopyr Concentration (ppb)	1321	2760	1705	1205	210	2880	1119	2470	1850	1295
Middle Triclopyr Concentration (ppb)	855	315	525	751	100	355	1280	675	510	385
Surface Triclopyr Concentration (ppb)	729	335	440	892	40	110	913	265	555	415
Bottom Endothall Concentration (ppb)	1216	105	913	206	149	3983	323	6773	2126	53
Middle Endothall Concentration (ppb)	1018	14	222	64	153	194	288	55	70	20
Surface Endothall Concentration (ppb)	1376	201	213	64	95	38	165	57	10	49

Station 25	0 HAT	1 HAT	3 HAT	6 HAT	8 HAT	10 HAT	12 HAT	24 HAT	33 HAT	48 HAT
Bottom Triclopyr Concentration (ppb)	2421	2920	710	1520	150	2250	1344	1155	1005	
Middle Triclopyr Concentration (ppb)	817	415	665	797	100	1665	1603	505	670	
Surface Triclopyr Concentration (ppb)	758	295	640	805	215	1005	1064	410	580	455
Bottom Endothall Concentration (ppb)	6841	350	431	10381	254	13502	686	390	226	
Middle Endothall Concentration (ppb)	1261	184	387	156	76	641	925	130	169	
Surface Endothall Concentration (ppb)	1372	54	497	194	234	206	413	151	148	413

Table A2. Triclopyr and endothall (µg/L) concentrations for all internal stations within Plot 3. Results are further divided by water column. Blank cells denote missing samples or those that were never taken.

Station 1	**0 HAT**	**1 HAT**	**2.5 HAT**	**6 HAT**	**7 HAT**	**19 HAT**	**46 HAT**	**68 HAT**
Bottom Triclopyr Concentration (ppb)	1510	1990	757	3913	1830	851	590	445
Middle Triclopyr Concentration (ppb)	269	190	978	2721	2520	738	505	405
Surface Triclopyr Concentration (ppb)	216	4975	609	1440	835	703		525
Bottom Endothall Concentration (ppb)	2050	919	610	46	2044	563	141	96
Middle Endothall Concentration (ppb)	1229	208	340	1814	2580	701	53	14
Surface Endothall Concentration (ppb)	1096	2925	0	1745	448	844		162

Station 2	**0 HAT**	**1 HAT**	**2.5 HAT**	**6 HAT**	**7 HAT**	**19 HAT**	**46 HAT**	**68 HAT**
Bottom Triclopyr Concentration (ppb)	1857	2815	1868	3666	5135	468	630	425
Middle Triclopyr Concentration (ppb)	1405	860	1842	4322	3725	467	480	470
Surface Triclopyr Concentration (ppb)	704	905	2754	2799	1855	388	460	450
Bottom Endothall Concentration (ppb)	1766	1474	2976	551	9202	129	79	57
Middle Endothall Concentration (ppb)	1635	724	3082	138	5257	105	0	86
Surface Endothall Concentration (ppb)	1035	714	2781	723	1943	91	7	112

Station 3	**0 HAT**	**1 HAT**	**2.5 HAT**	**6 HAT**	**7 HAT**	**19 HAT**	**46 HAT**	**68 HAT**
Bottom Triclopyr Concentration (ppb)	1262	370	1890	1379	675	807	520	405
Middle Triclopyr Concentration (ppb)	282	55	298	760	65	485	400	370
Surface Triclopyr Concentration (ppb)	330	15	409	862	25	544	470	435
Bottom Endothall Concentration (ppb)	1701	230	1703	84	396	598	10	7
Middle Endothall Concentration (ppb)	1362	121	67	385	72	108	0	0
Surface Endothall Concentration (ppb)	1470	52	57	96	25	38	1	0

Station 4	**0 HAT**	**1 HAT**	**2.5 HAT**	**6 HAT**	**7 HAT**	**19 HAT**	**46 HAT**	**68 HAT**
Bottom Triclopyr Concentration (ppb)	247	350	1461	825	1410	576	205	365
Middle Triclopyr Concentration (ppb)	359	15	947	705	55	444	375	375
Surface Triclopyr Concentration (ppb)	277	0	318	744	35	480	555	365
Bottom Endothall Concentration (ppb)	1868	406	1625	287	1131	323	27	0
Middle Endothall Concentration (ppb)	1520	48	295	41	27	45	0	28
Surface Endothall Concentration (ppb)	1996	16	30	59	0	50	14	17

Station 5	**0 HAT**	**1 HAT**	**2.5 HAT**	**6 HAT**	**7 HAT**	**19 HAT**	**46 HAT**	**68 HAT**
Bottom Triclopyr Concentration (ppb)	1652	2415	553	815	155	779	650	350
Middle Triclopyr Concentration (ppb)	557	35	435	926	0	374	615	380
Surface Triclopyr Concentration (ppb)	531	0	304	997	10	309	585	320
Bottom Endothall Concentration (ppb)	2011	1379	157	102	159	574	11	20
Middle Endothall Concentration (ppb)	2058	101	82	4457	8	100	12	0
Surface Endothall Concentration (ppb)	1530	0	6	5944	29	27	0	0

Station 6	0 HAT	1 HAT	2.5 HAT	6 HAT	7 HAT	19 HAT	46 HAT	68 HAT
Bottom Triclopyr Concentration (ppb)	982	70	407	1455	255	482	955	380
Middle Triclopyr Concentration (ppb)	735	15	316	838	25	404	360	405
Surface Triclopyr Concentration (ppb)	408	5	284	878	15	477	675	355
Bottom Endothall Concentration (ppb)	982	156	73	75	208	114	51	0
Middle Endothall Concentration (ppb)	1479	40	108	6618	47	62	5	0
Surface Endothall Concentration (ppb)	1604	19	7	102	29	80	7	5

Station 7	0 HAT	1 HAT	2.5 HAT	6 HAT	7 HAT	19 HAT	46 HAT	68 HAT
Bottom Triclopyr Concentration (ppb)	895	885	1566	858	485	461	425	415
Middle Triclopyr Concentration (ppb)	699	740	852	795	210	389	455	305
Surface Triclopyr Concentration (ppb)	559	1155	2035	807	345	377	560	320
Bottom Endothall Concentration (ppb)	1309	868	1614	108	510	70	0	0
Middle Endothall Concentration (ppb)	1525	783	475	39	131	54	0	7
Surface Endothall Concentration (ppb)	1245	1075	840	48	167	64	31	0

Station 8	0 HAT	1 HAT	2.5 HAT	6 HAT	7 HAT	19 HAT	46 HAT	68 HAT
Bottom Triclopyr Concentration (ppb)	2214	190	864	804	230	366	490	390
Middle Triclopyr Concentration (ppb)	864		420	786	90	365	620	380
Surface Triclopyr Concentration (ppb)	1217	15	445	900	130	365	575	335
Bottom Endothall Concentration (ppb)	3239	328	826	51	158	47	0	56
Middle Endothall Concentration (ppb)	1457		306	31	66	46	21	0
Surface Endothall Concentration (ppb)	1625	81	120	224	76	30	6	0

Station 15	0 HAT	1 HAT	2.5 HAT	6 HAT	7 HAT	19 HAT	46 HAT	68 HAT
Bottom Triclopyr Concentration (ppb)		695						
Middle Triclopyr Concentration (ppb)								
Surface Triclopyr Concentration (ppb)	560	370	845	595	1155	1330	200	35
Bottom Endothall Concentration (ppb)		874						
Middle Endothall Concentration (ppb)								
Surface Endothall Concentration (ppb)	1056	945	1175	893	2349	2491	629	75

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

A field demonstration was developed linking herbicide application methods with site-specific water exchange patterns to selectively control infestations of Eurasian watermilfoil (EWM) and curlyleaf pondweed (CLP) in Noxon Rapids Reservoir, MT. Objectives of this work are to evaluate species-selective control of these invasive plants employing innovative herbicide application techniques; and to provide recommendations for invasive plant management in the reservoir, and similar impoundments in the Pacific Northwest. Bulk water exchange patterns occurring in plant stands selected for herbicide applications were determined using rhodamine WT (RWT) tracer dye. These site-specific patterns were matched with appropriate herbicide application rates required to selectively control target plants. Treatments were conducted using a variable-depth injection system, simultaneously applying RWT and herbicides to provide maximum chemical contact time around plants stands. In late July 2009, two plots (8.2-11.5 ha) were treated using combinations of RWT (10 µg/L), triclopyr (1300 - 1850 µg/L), and endothall (1890 - 2500 µg/L). Dye (in situ) and herbicide residues (via enzyme-linked immunosorbent assay) were measured through the water column, inside and outside of the plots. Applications were conducted to coincide with the minimum reservoir discharge patterns. Whole plot water exchange half-lives ranged from 16 to 33 hr. Herbicide residues were highest around plants growing in the lower half of the water column (19-48 hr). External herbicide dissipation patterns were below levels of environmental/human health concerns. Treatments provided selective control of EWM for two years (> 85%) and CLP for one year (> 75%). Native plant species richness and dissolved oxygen levels were unchanged in treatment plots during the study period.

15. SUBJECT TERMS

Aquatic herbicides	Eurasian watermilfoil	Water exchange patterns
Curlyleaf pondweed	Invasive plant species	
	Noxon Rapids Reservoir, Montana	

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